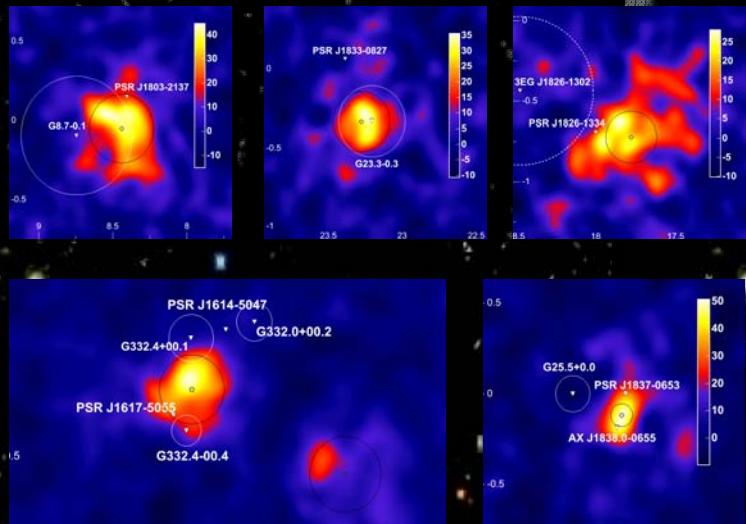


... and Observational Results



PART 2

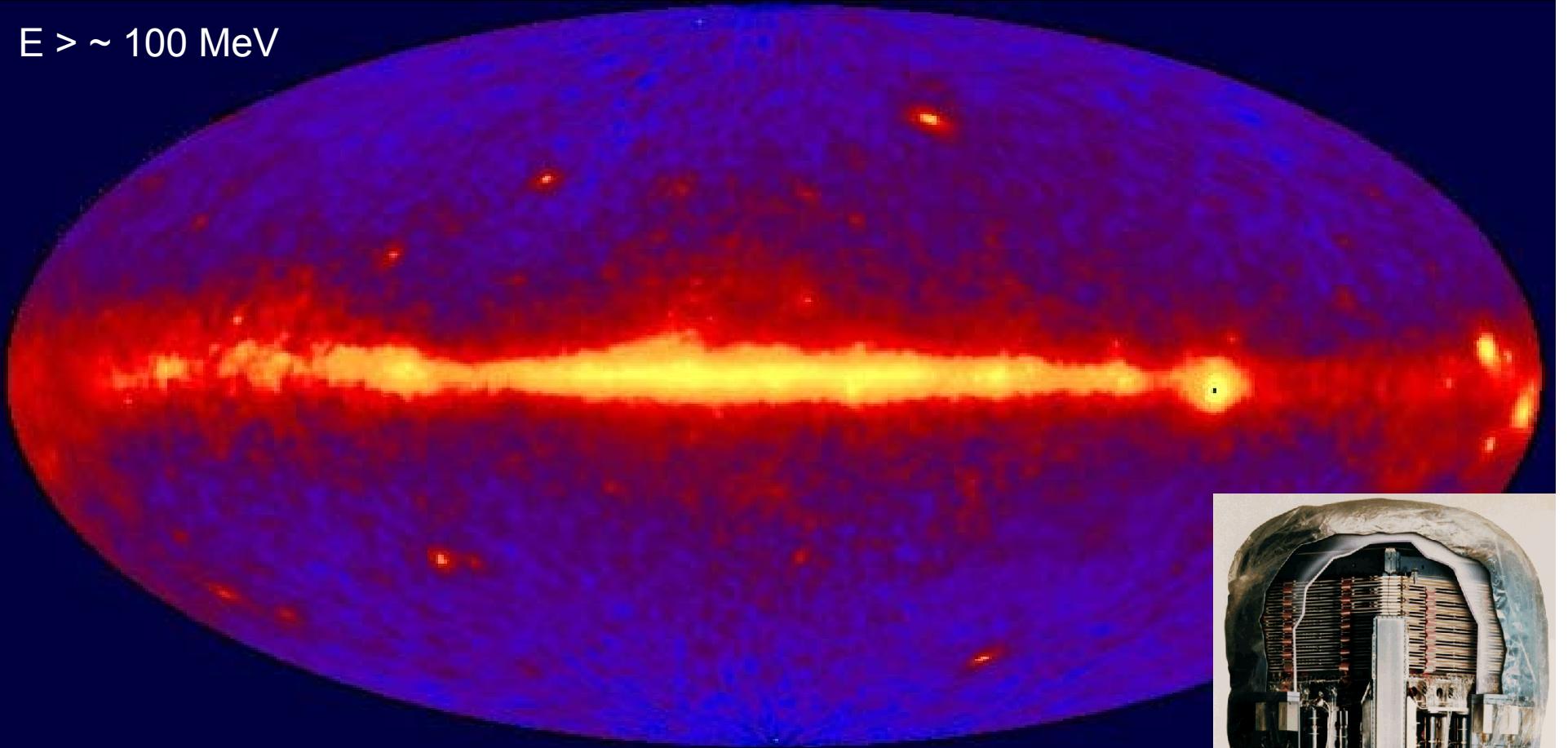
- Counting TeV Sources
- Supernova Remnants
- The Galactic Plane
- Galactic Center Region
- The Extragalactic BG Light

G.Hermann
MPIK Heidelberg



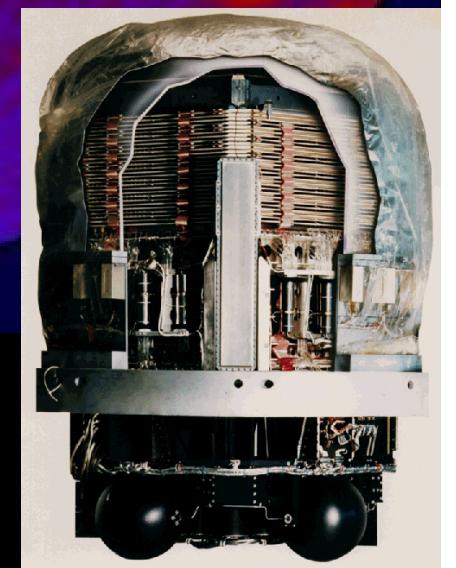
The High-Energy γ -Ray Sky by EGRET

$E > \sim 100$ MeV

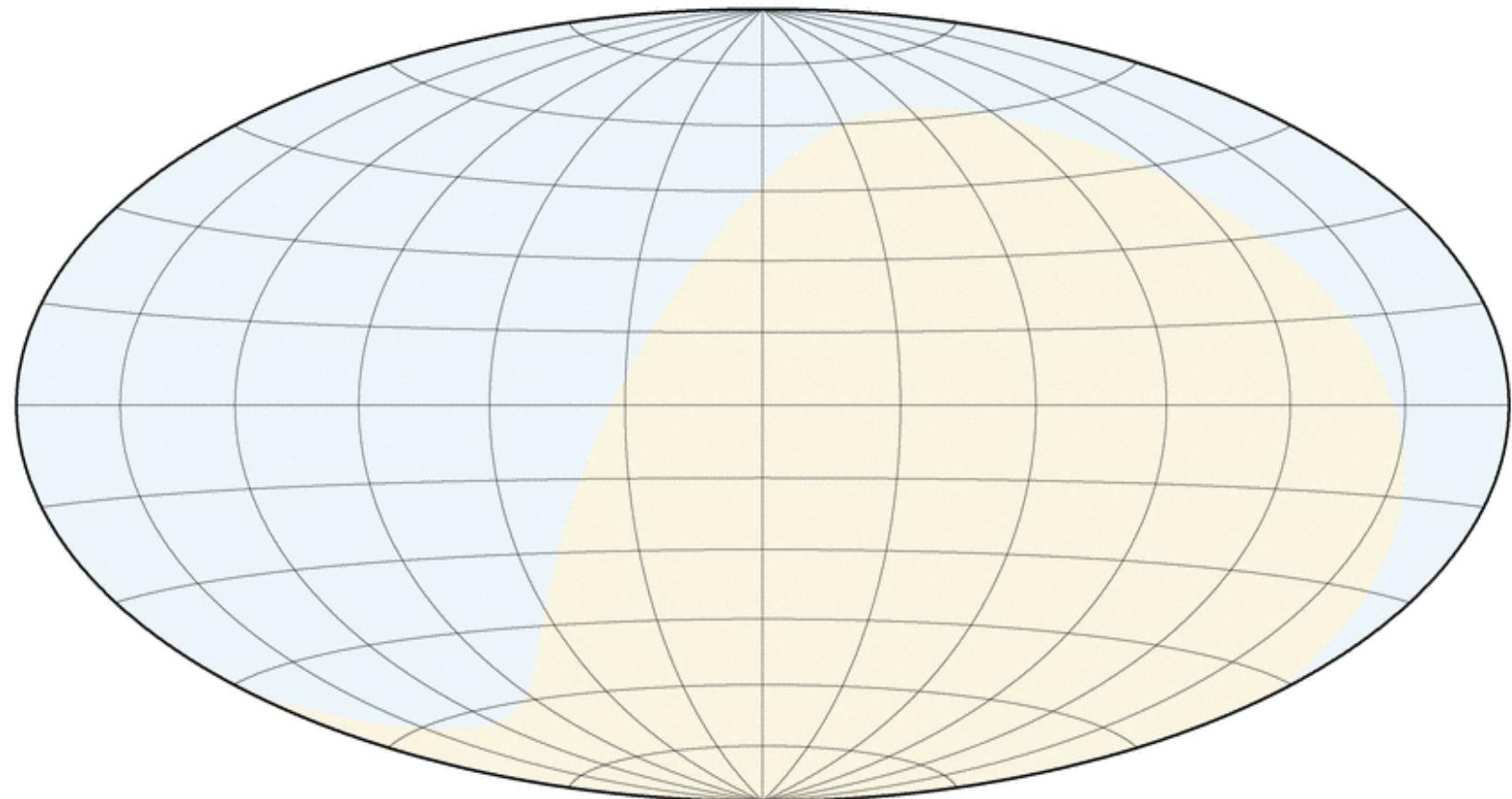


271 Sources (66 blazars and 170 unidentified)
+ diffuse galactic emission (CR interaction w/ medium)
+ (maybe) extra-galactic diffuse emission

3rd EGRET catalogue (Hartmann 1999)



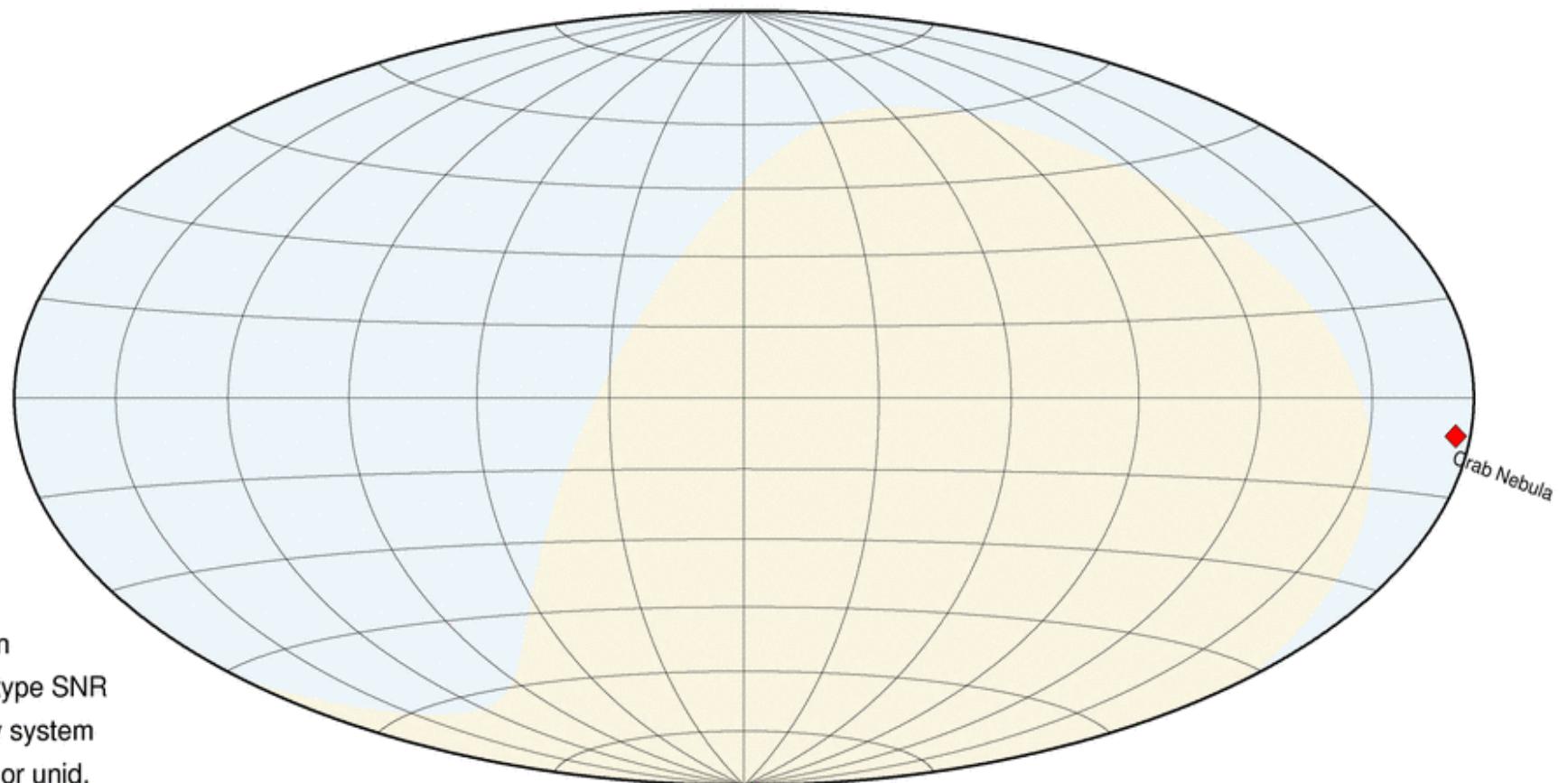
The High-Energy Gamma Ray Sky (1988)



Background colours indicating northern / southern sky

The High-Energy Gamma Ray Sky (1989)

(Galactic coordinates)



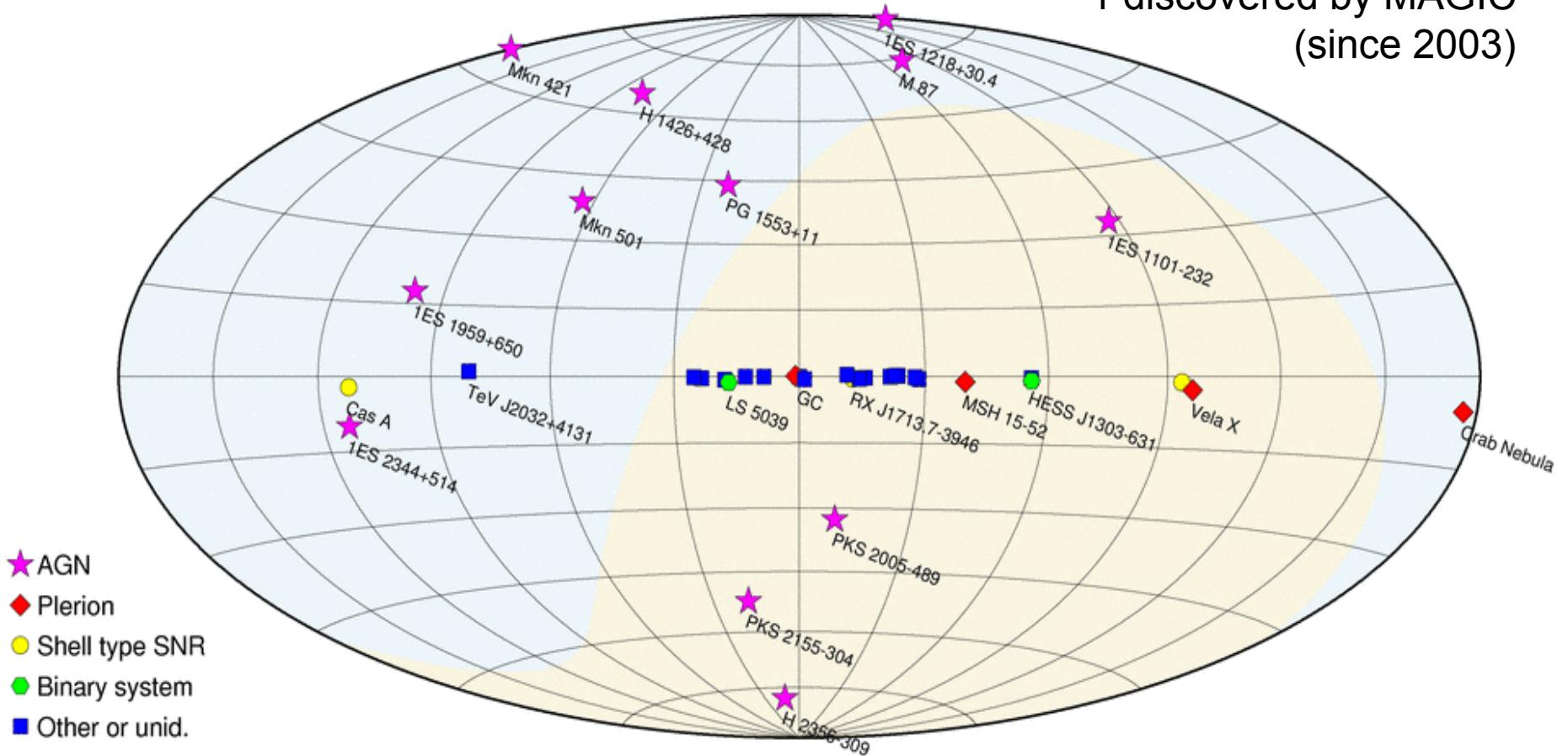
Background colours indicating northern / southern sky

The High-Energy Gamma Ray Sky (2006)

39 sources ($E > 100$ GeV)

(Galactic coordinates)

~ 25 discovered by H.E.S.S.
1 discovered by MAGIC
(since 2003)



Background colours indicating northern / southern sky

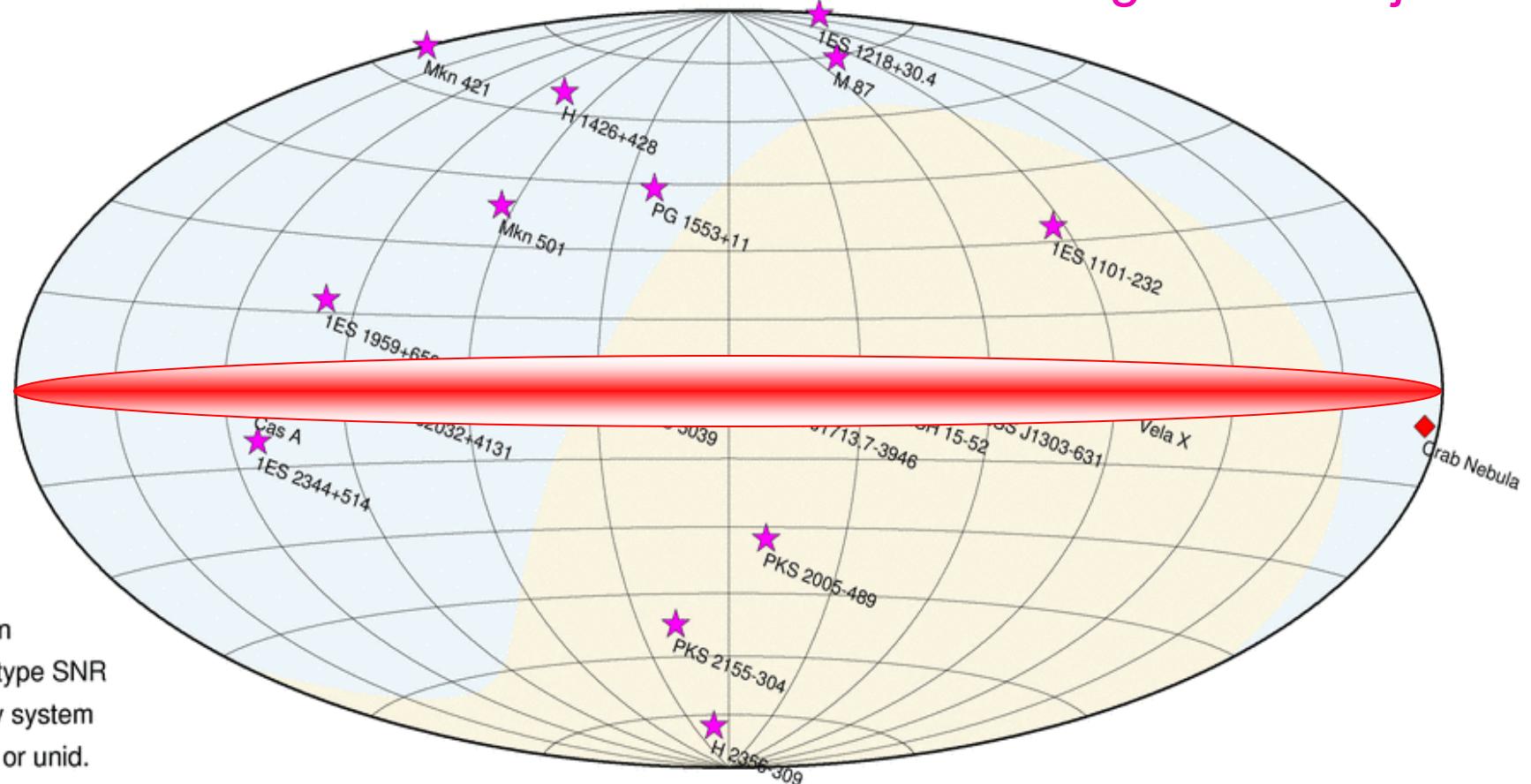
Courtesy K.Bernlöhr, MPI-K

The High-Energy Gamma Ray Sky (2006)

Galactic Sources

(Galactic coordinates)

Extragalactic Objects



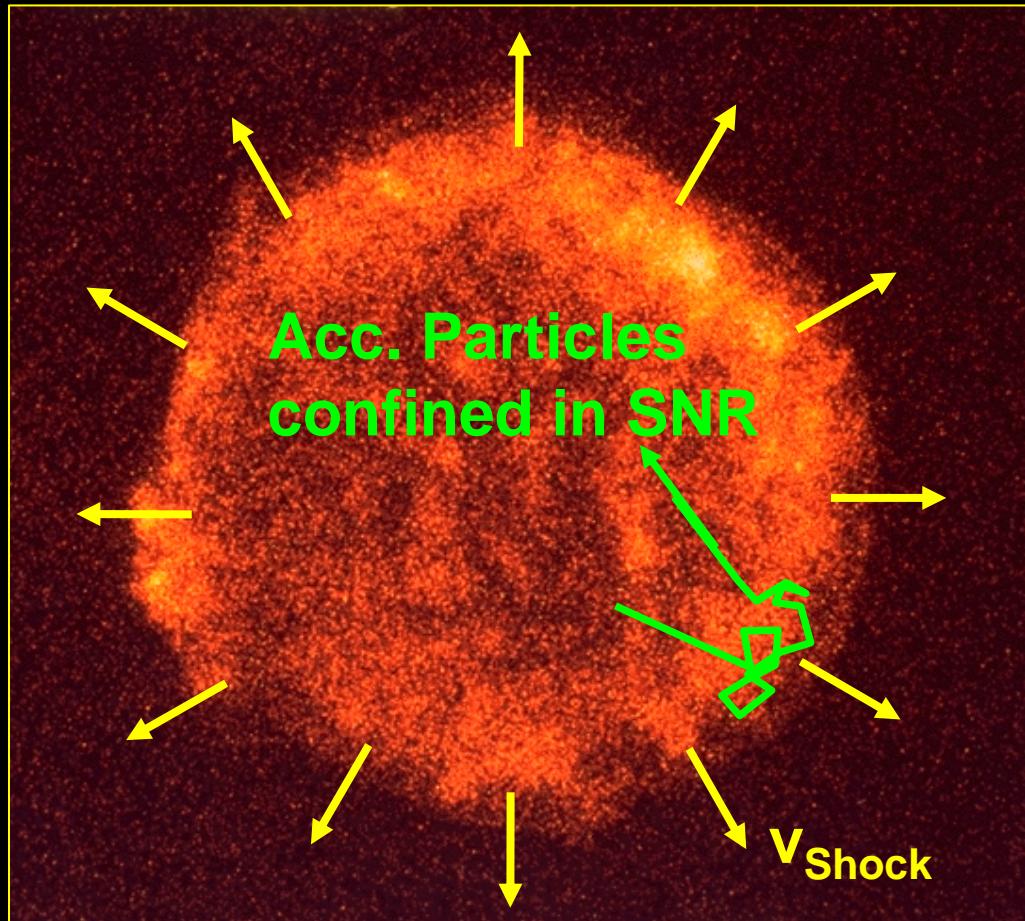
Courtesy K.Bernlöhr, MPI-K

Searching for the Cosmic Particle Accelerators

- TeV Source Statistics
- Supernova Remnants
- The Galactic Plane
- Galactic Center Region
- The Extragalactic BG Light



Shock Acceleration in SNRs



Elastic collisions of particles at the shock front

Gamma Ray Emission
from π^0 Decay after collision w/ ambient matter

Drury, Aharonian, Völk (1994)

$$F_\gamma(> 1 \text{ TeV}) \sim \theta E_{51} n_1 d_{\text{kpc}}^{-2}$$

Universal Law
 $dN/dE \sim E^{-\alpha}$; $\alpha \sim 2.1$

SNRs as **the** sources of the galactic Cosmic Rays ?

SNRs in the Light of TeV γ -Rays (< 2004)



Supernova	d [kpc]	Flux [Crab Units]	Exp.
SN 1006	1.4 – 2.1	0.5	CANGAROO
RX J1713.7...	1 – 6	0.7	CANGAROO
Cassiopeia A	3.3 – 3.7	0.03	HEGRA

Cassiopeia-A by HEGRA

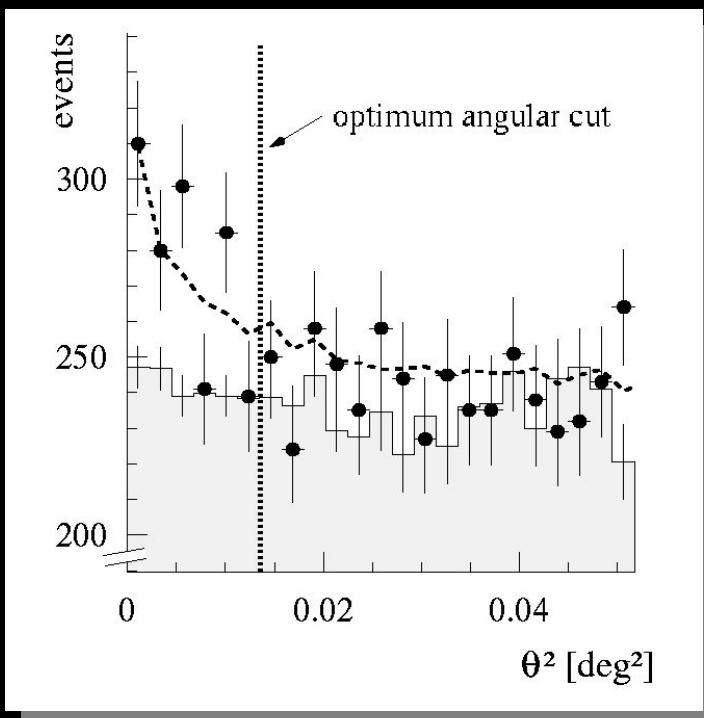
SN Explosion in 1680

$d \sim 3.3 - 3.7 \text{ kpc}$

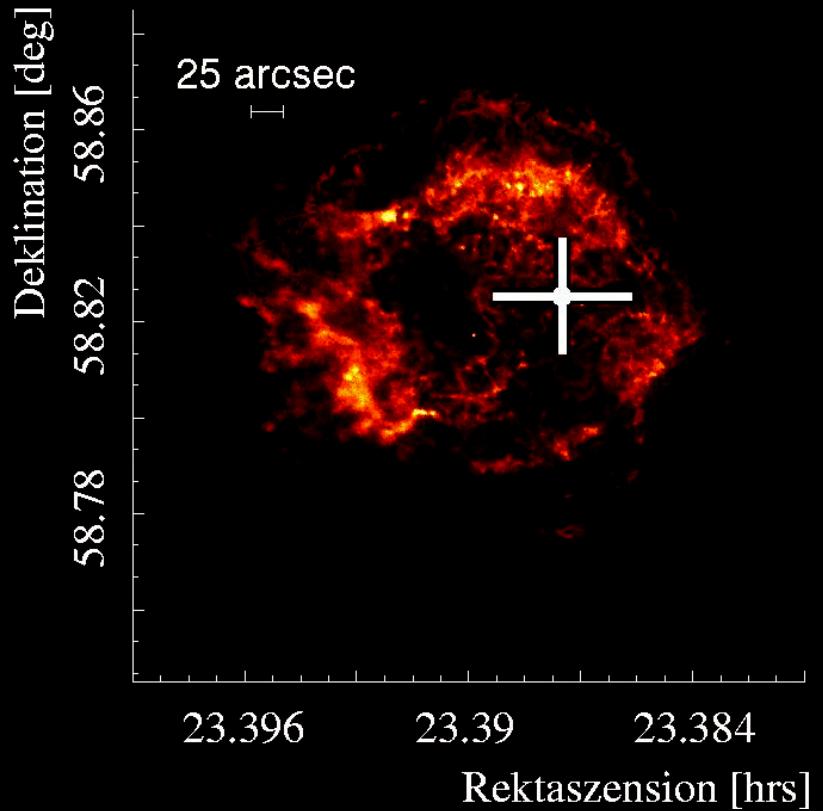
Very deep observation: **232 h (patience)**

3 years of data

5σ signal at 0.03 Crab level

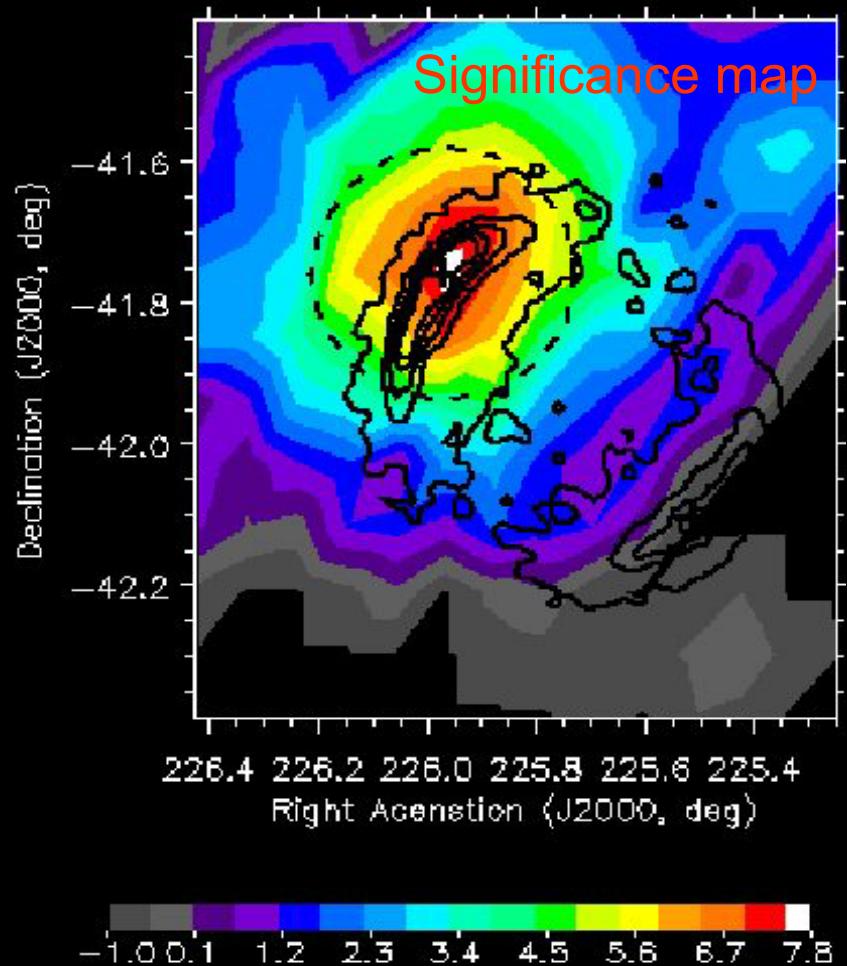


Pühlhofer (1999)



C.o.g. of gamma emission
(diameter of SNR only
3-4 arc-min; can't
resolve details)

SN 1006 by CANGAROO

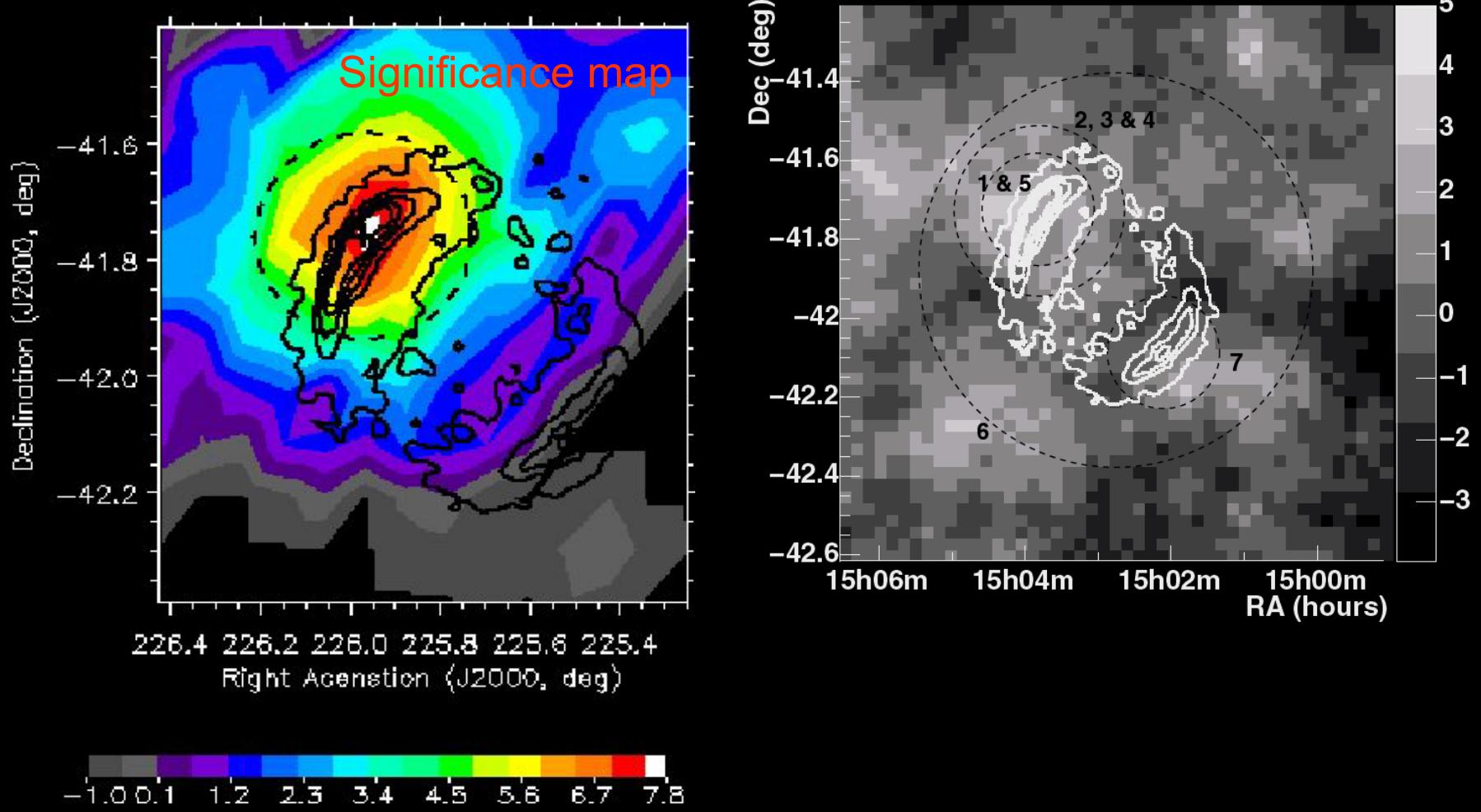


Two generations single dish telescopes:

3.8 m 7.7σ
10 m 6.5σ

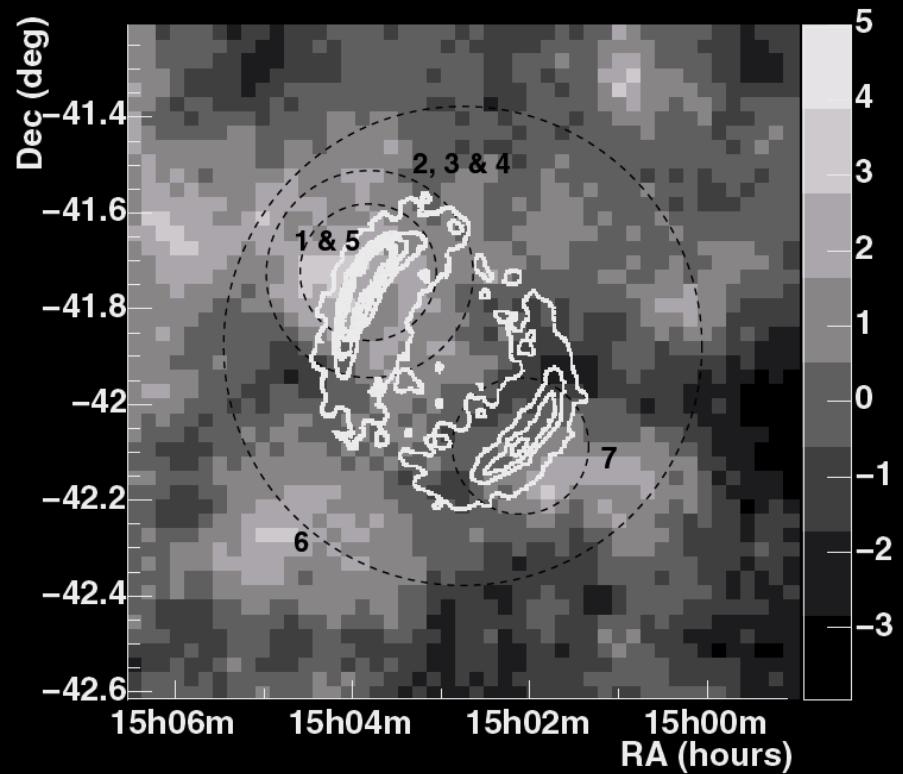
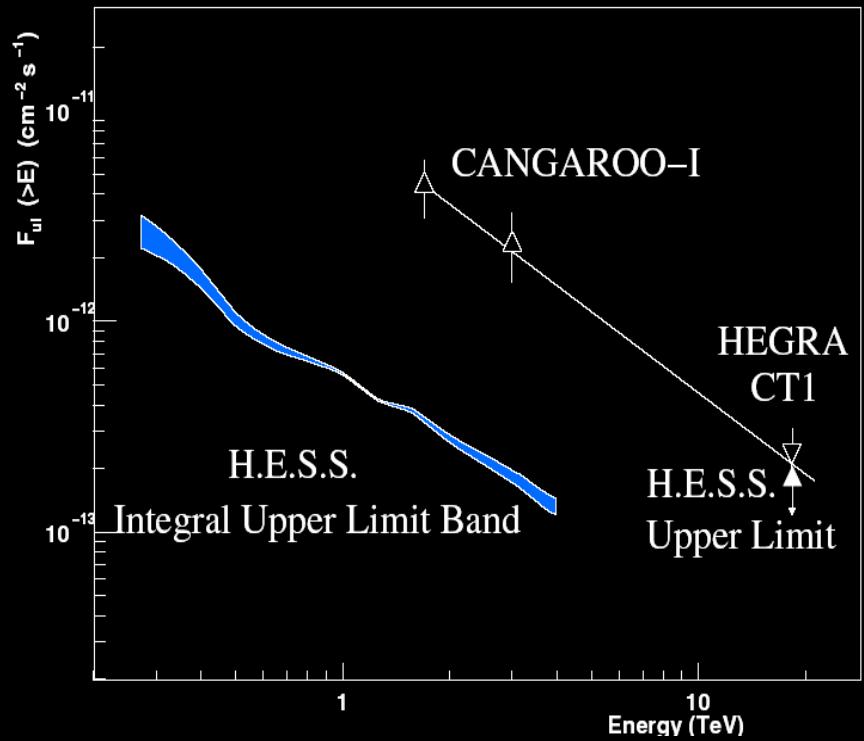
Tanimori et al. 1998, 2001

SN 1006 by CANGAROO & H.E.S.S.



H.E.S.S., Aharonian A&A437, (2005)

SN 1006 by CANGAROO & H.E.S.S.



H.E.S.S.

99.9 % U.L. is factor below CANGAROO
→ variable source ???

2006 preliminary: no signal with new
CANGAROO telescopes

H.E.S.S., Aharonian A&A437 (2005)

SNRs in the Light of TeV Gamma-Rays

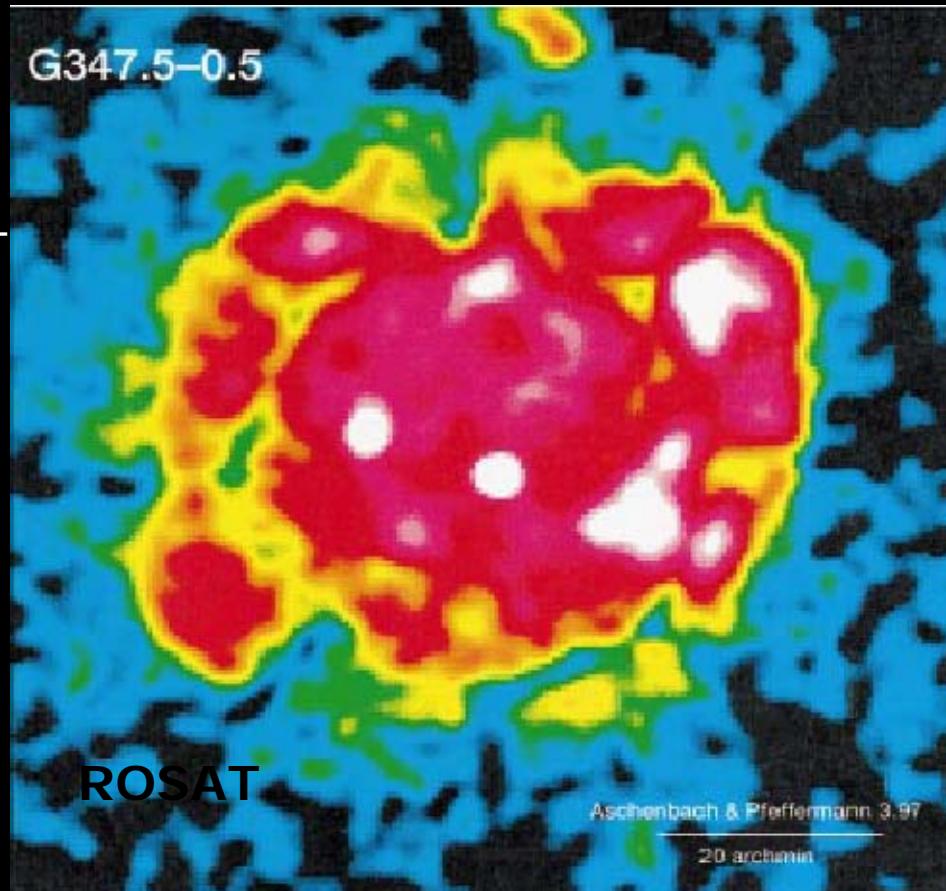


Supernova	d [kpc]	Flux [Crab Units]	Exp.
SN 1006	1.4 – 2.1	0.5	CANGAROO
RX J1713.7...	1 – 6	0.7	CANGAROO
Cassiopeia A	3.3 – 3.7	0.03	HEGRA



The SNR RX J1713.4-3946

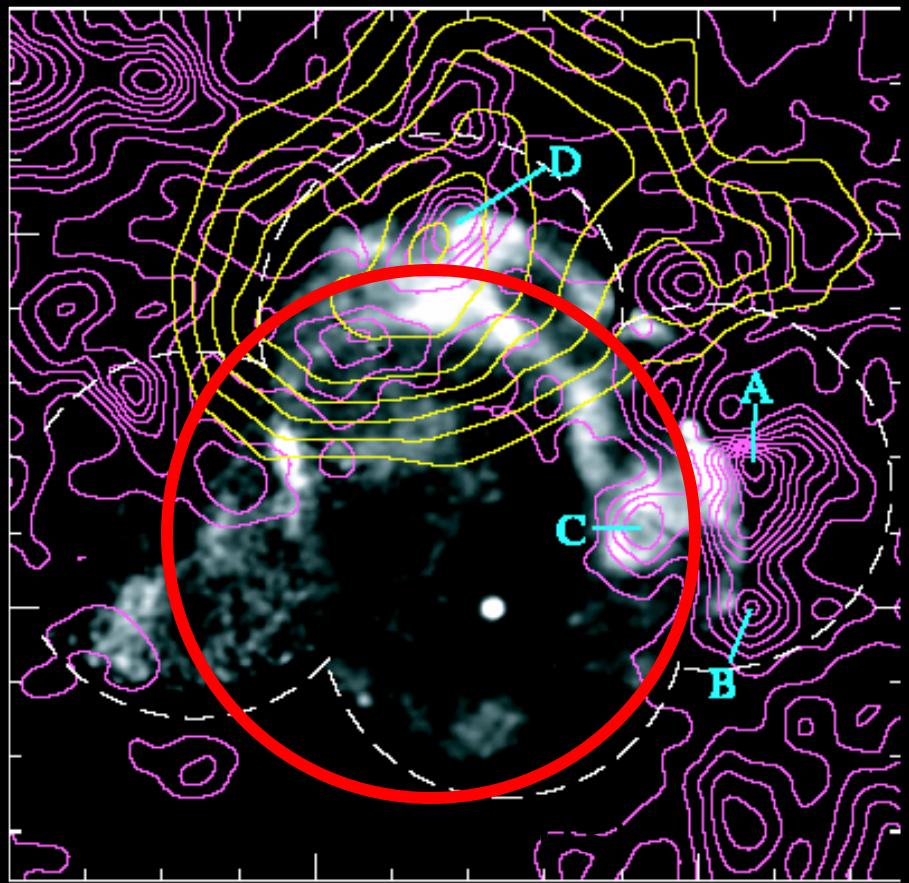
- Discovery: ROSAT All-Sky Survey
- X-ray emission mostly non-thermal
- Age: 1000 yrs (?)
 @ 1 kpc (?)



Aschenbach (1997)

RX J1713.4-3946 by CANGAROO

- Discovery: ROSAT All-Sky Survey
- X-ray emission mostly non-thermal
- Age: 1000 yrs (?)
 - @ 1 kpc (?)
- CANGAROO: TeV excess from western rim
- Recent CO data:
Interaction with MoC
distance of 1kpc
(under debate)



$$F_{\gamma}(> 1 \text{ TeV}) \sim \theta E_{51} n_1 d_{\text{kpc}}^{-2}$$

Cangaroo, Enemoto et al. (2002)

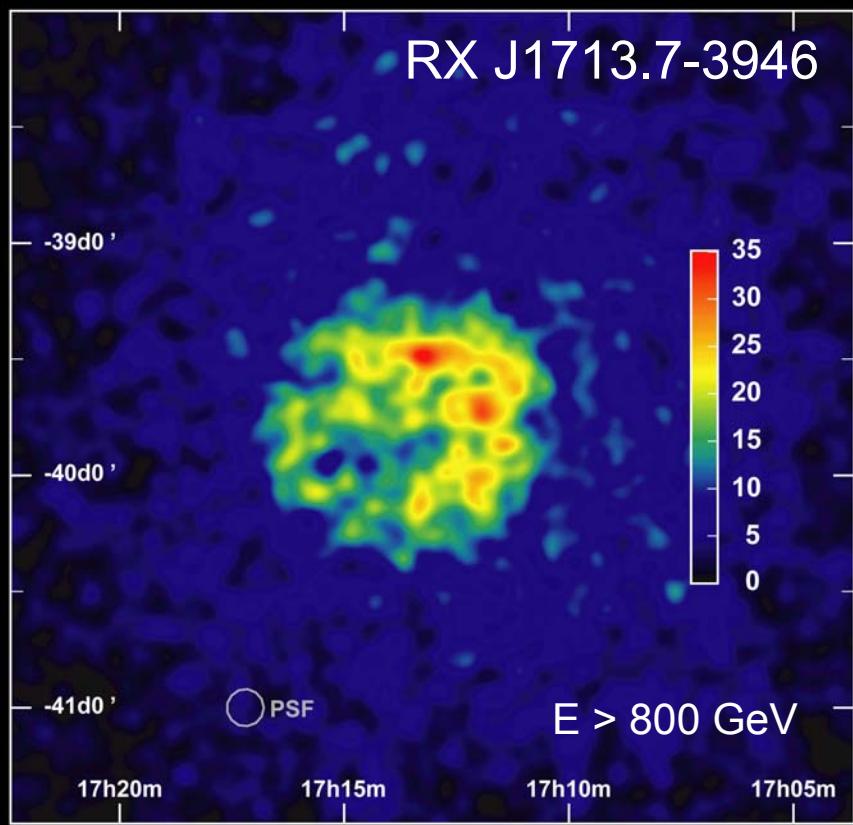


RX J1713.4-3946 by H.E.S.S.

18 hours with
2 telescopes in 2003

$\sim 20 \sigma$

Extension: ~ 1 deg
Flux: ~ 0.66 Crab



First-ever astronomical image of a TeV source
→ Nature 432, 75 (2004)

2004: ~ 33 hours of data
Smoothed image

-39 ~40 σ

-39.5

-40

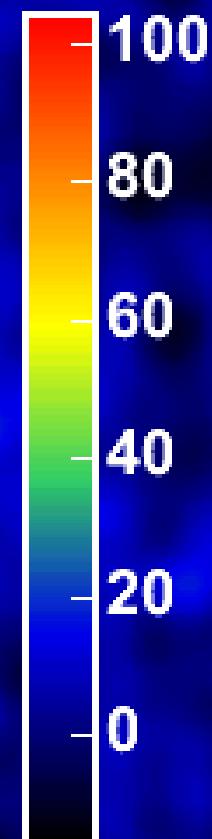
-40.5

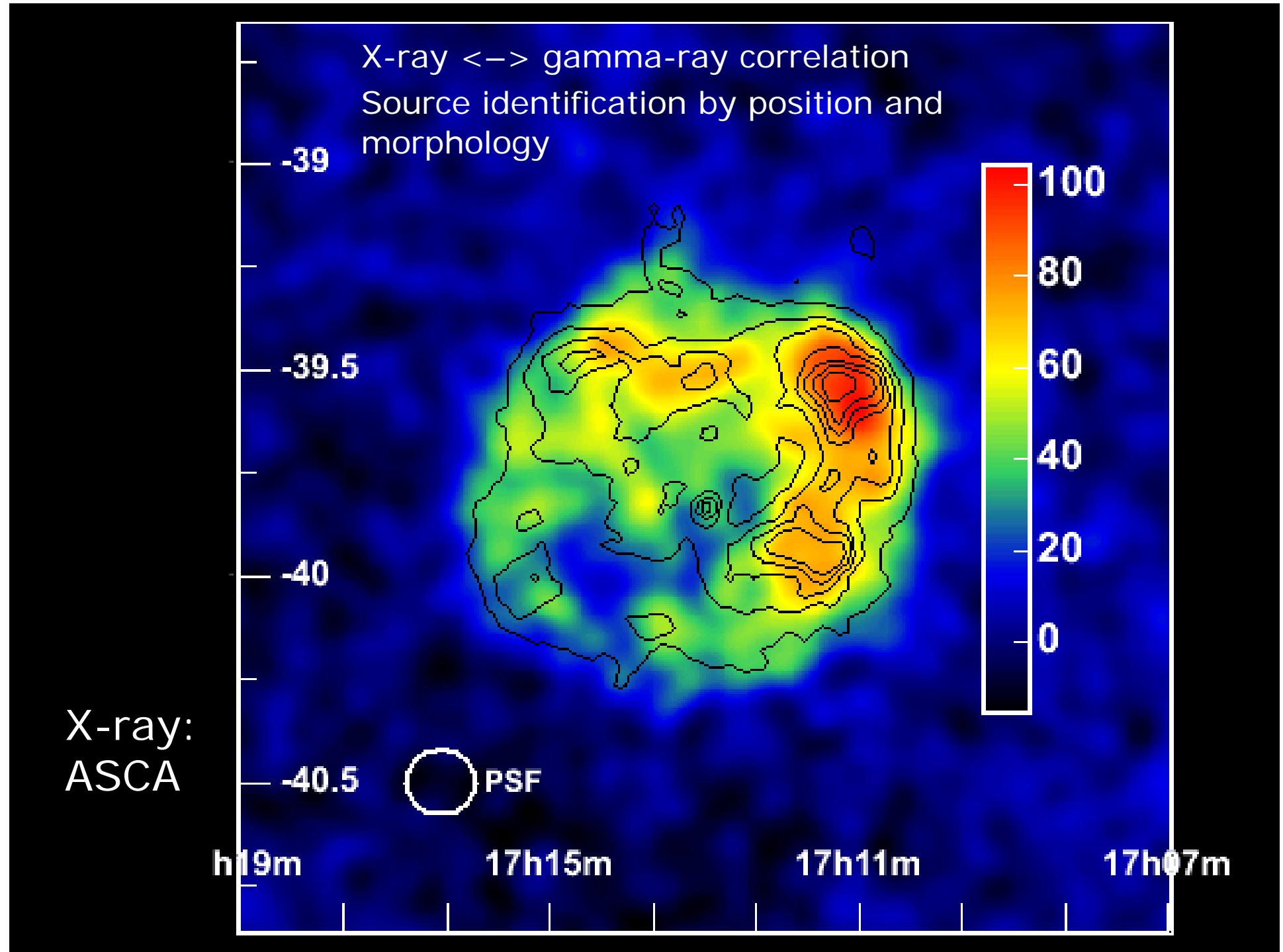
h19m

17h15m

17h11m

17h07m

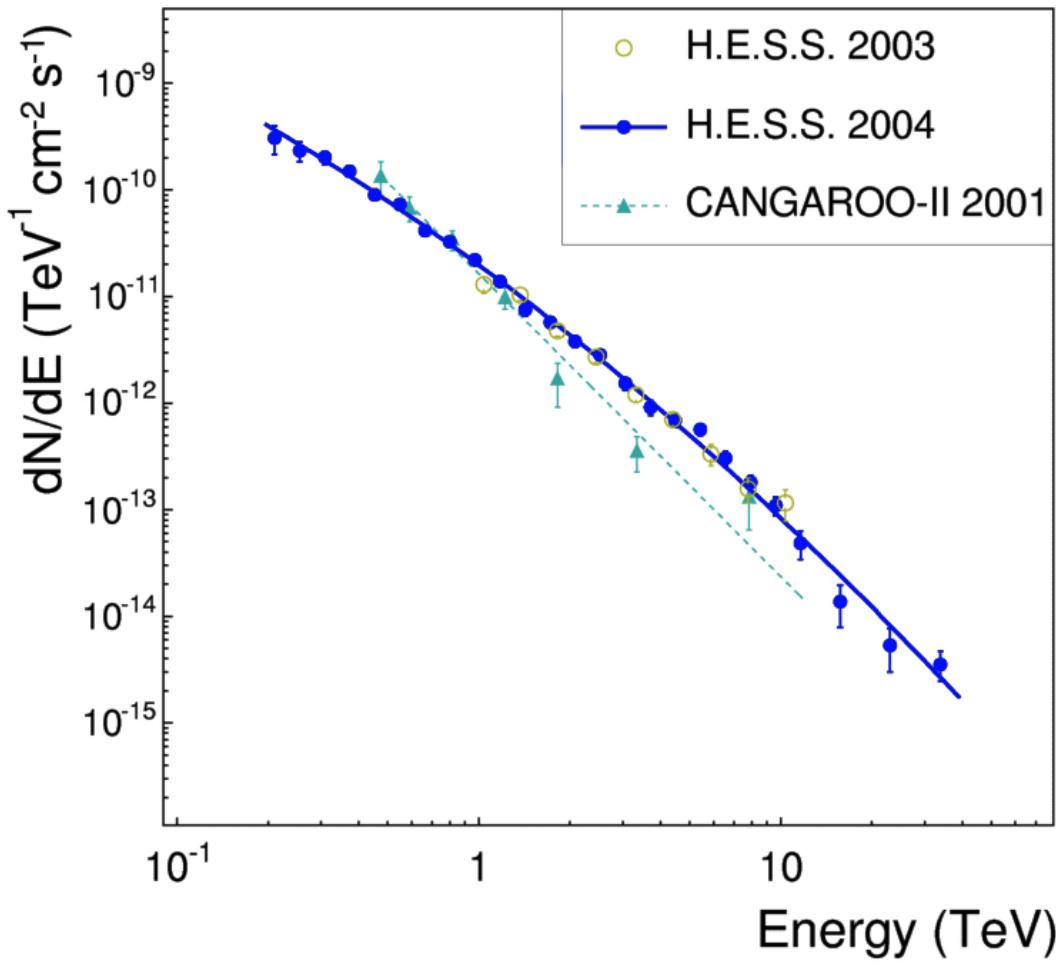




Is this one of the
Accelerators
of the
Galactic Cosmic Rays ???



RX 1713 Energy Spectrum



Flux: $\sim 66\%$ of Crab

Power law description:
Spectral index:

$2.2 + - 0.01 + - 0.15$

Cutoff or spectral break

6 sigma @ $E > 10$ TeV

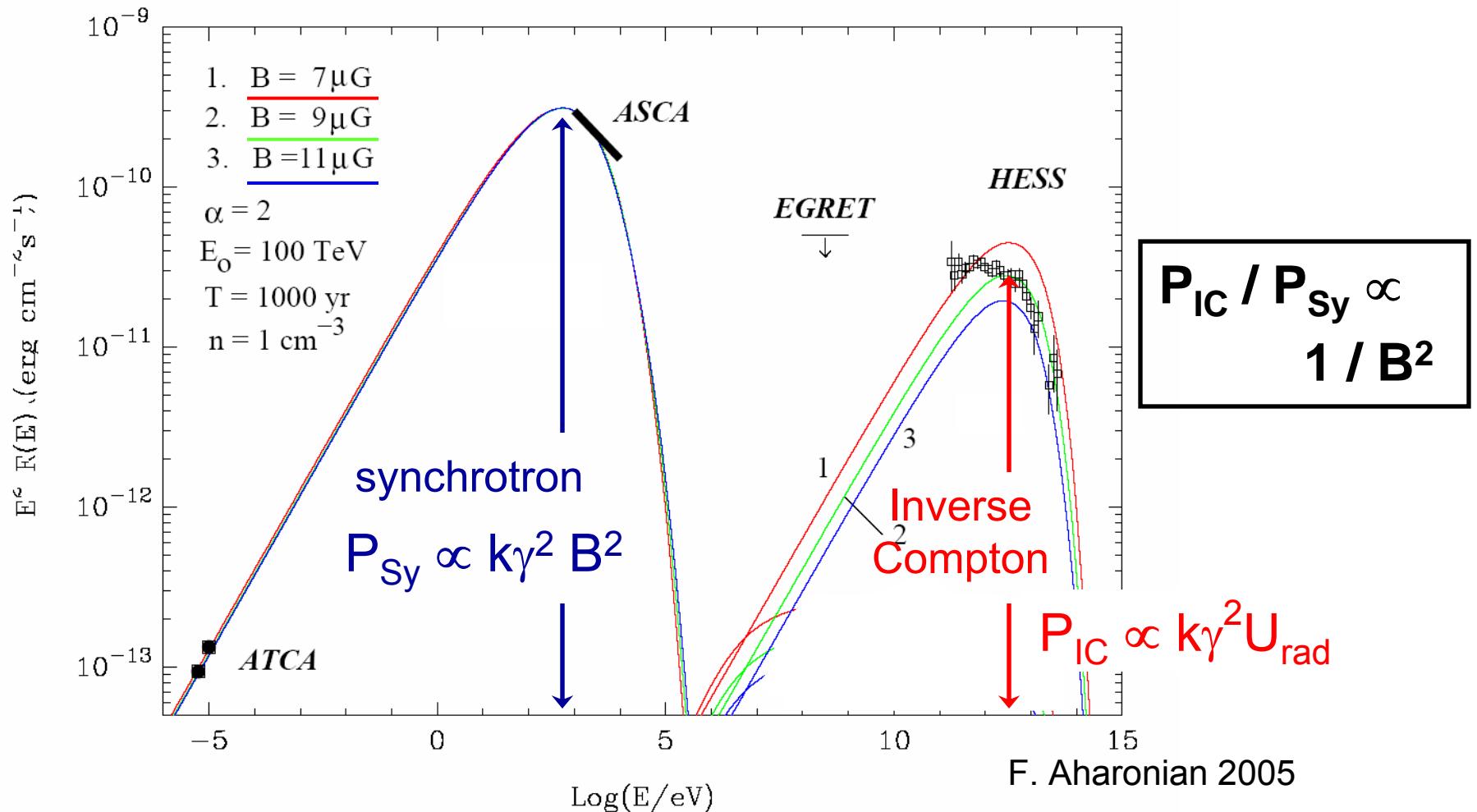
Consistent with shock
acceleration

Leptonic or hadronic
origin ???



Leptonic emission model for RX J1713

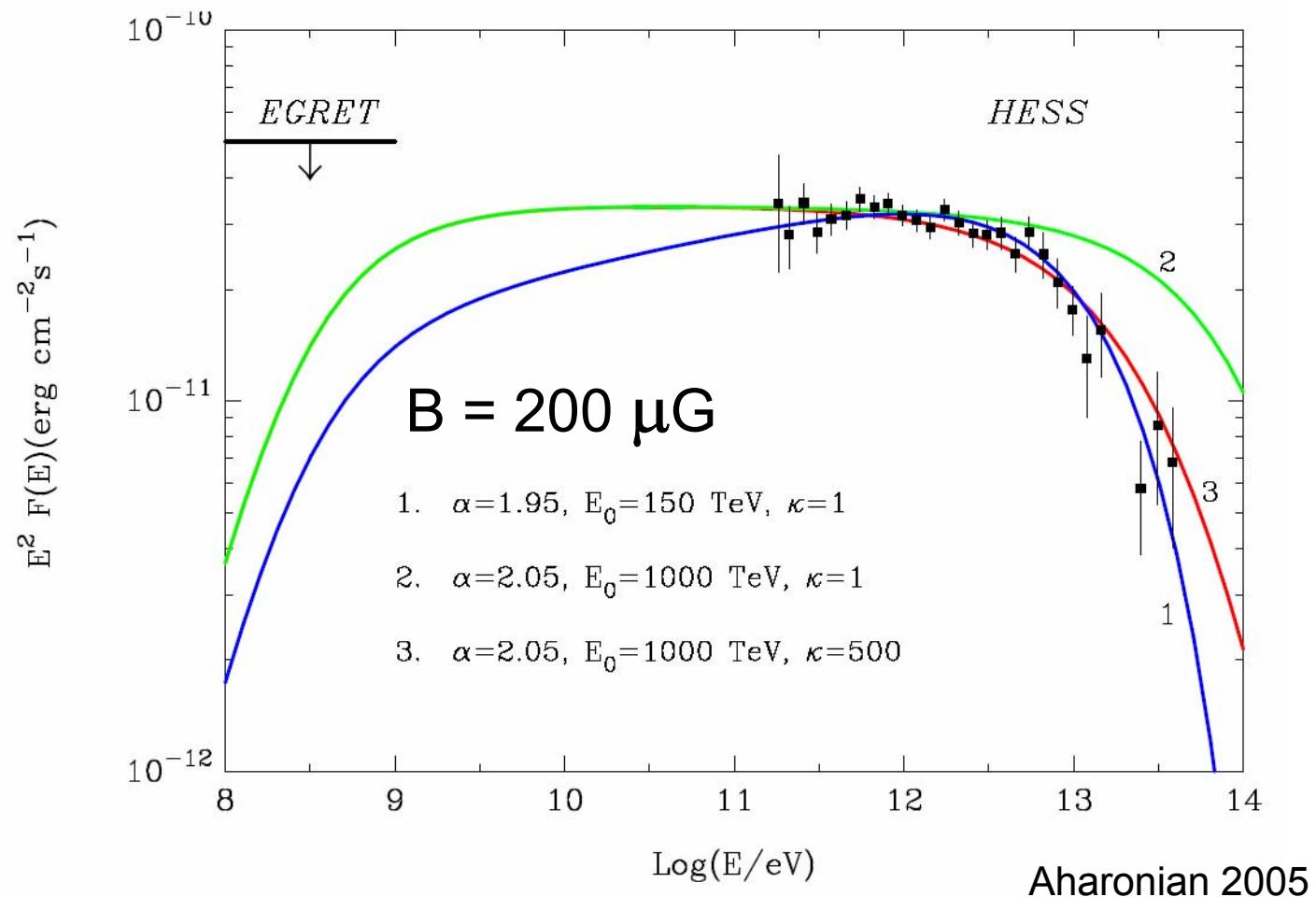
Assume Electrons: Synchrotron + Inverse Compton

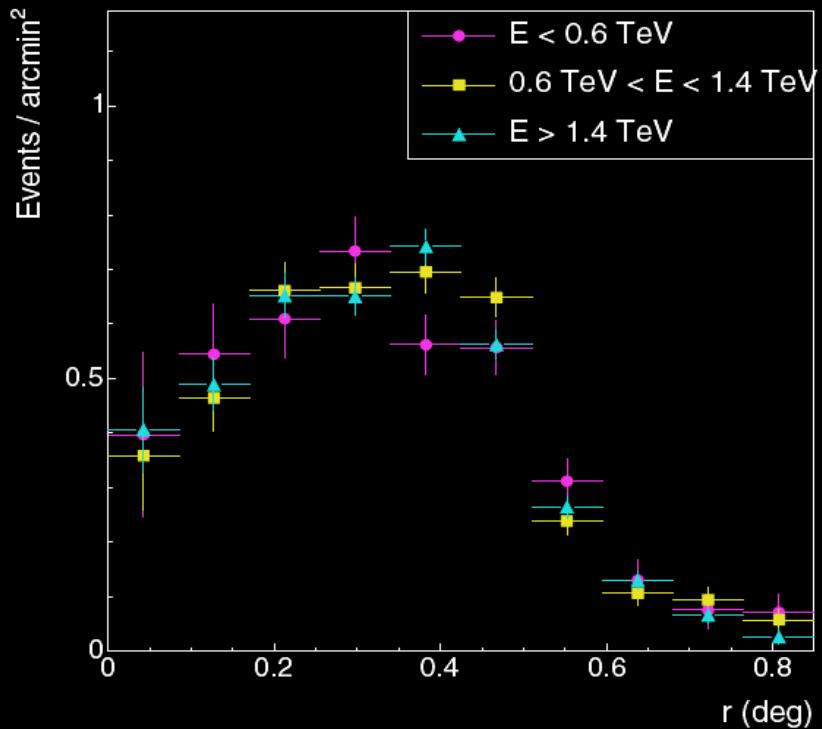




Hadronic emission model for RXJ 1713

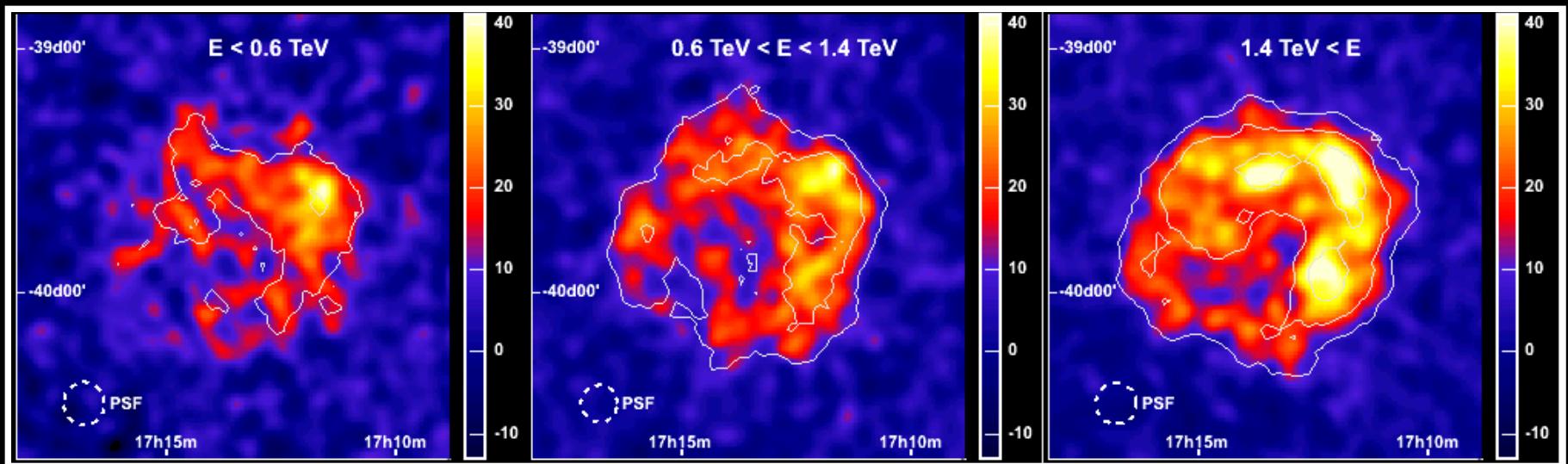
Collision of protons w/ ambient gas : $p + p \rightarrow \pi^0 + X$





RX J1713 Source Morphology

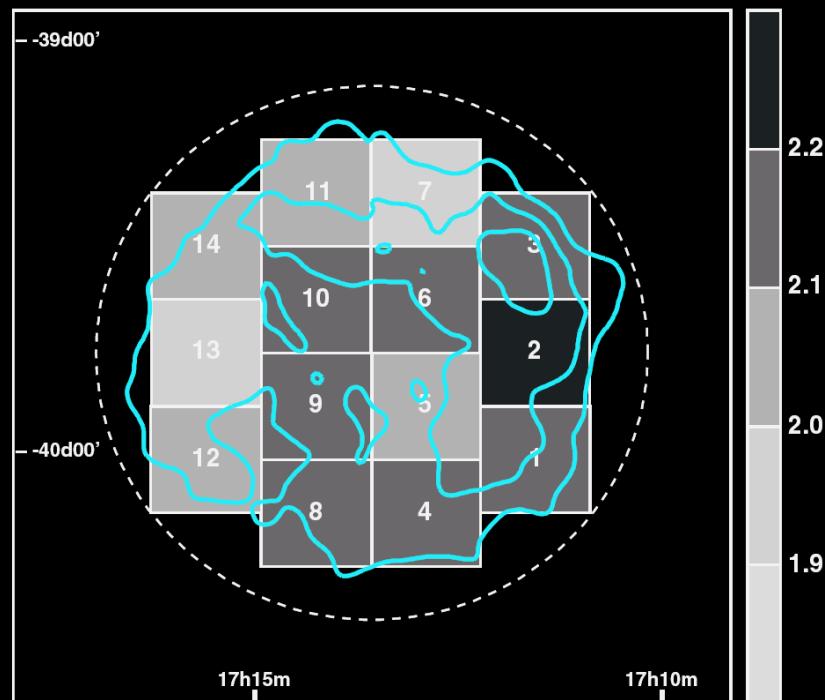
Shape of the TeV image does
not seem to change with energy



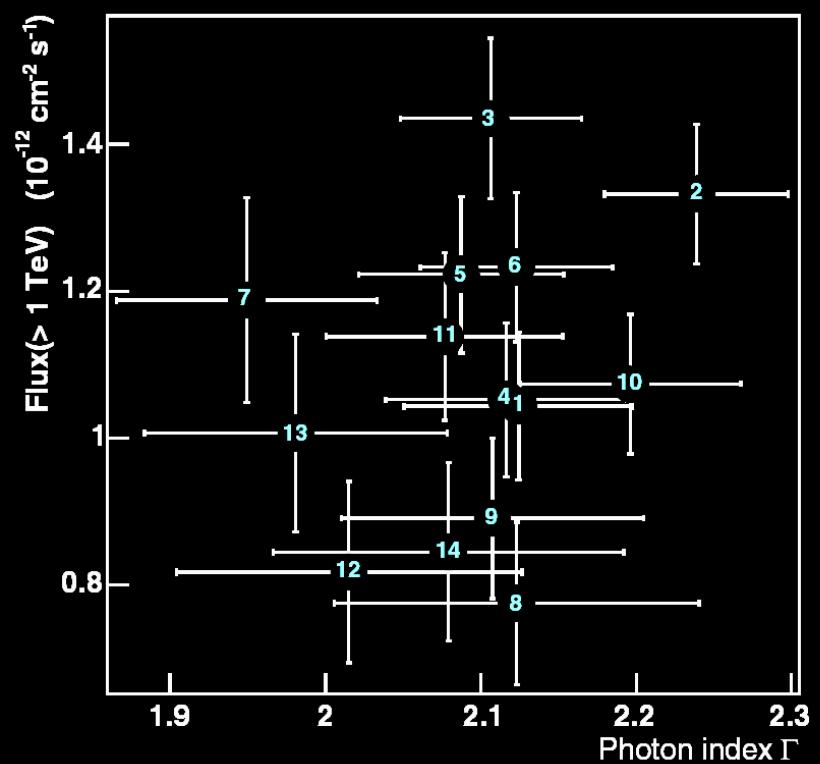


RX J1713 Source Morphology

Photon index



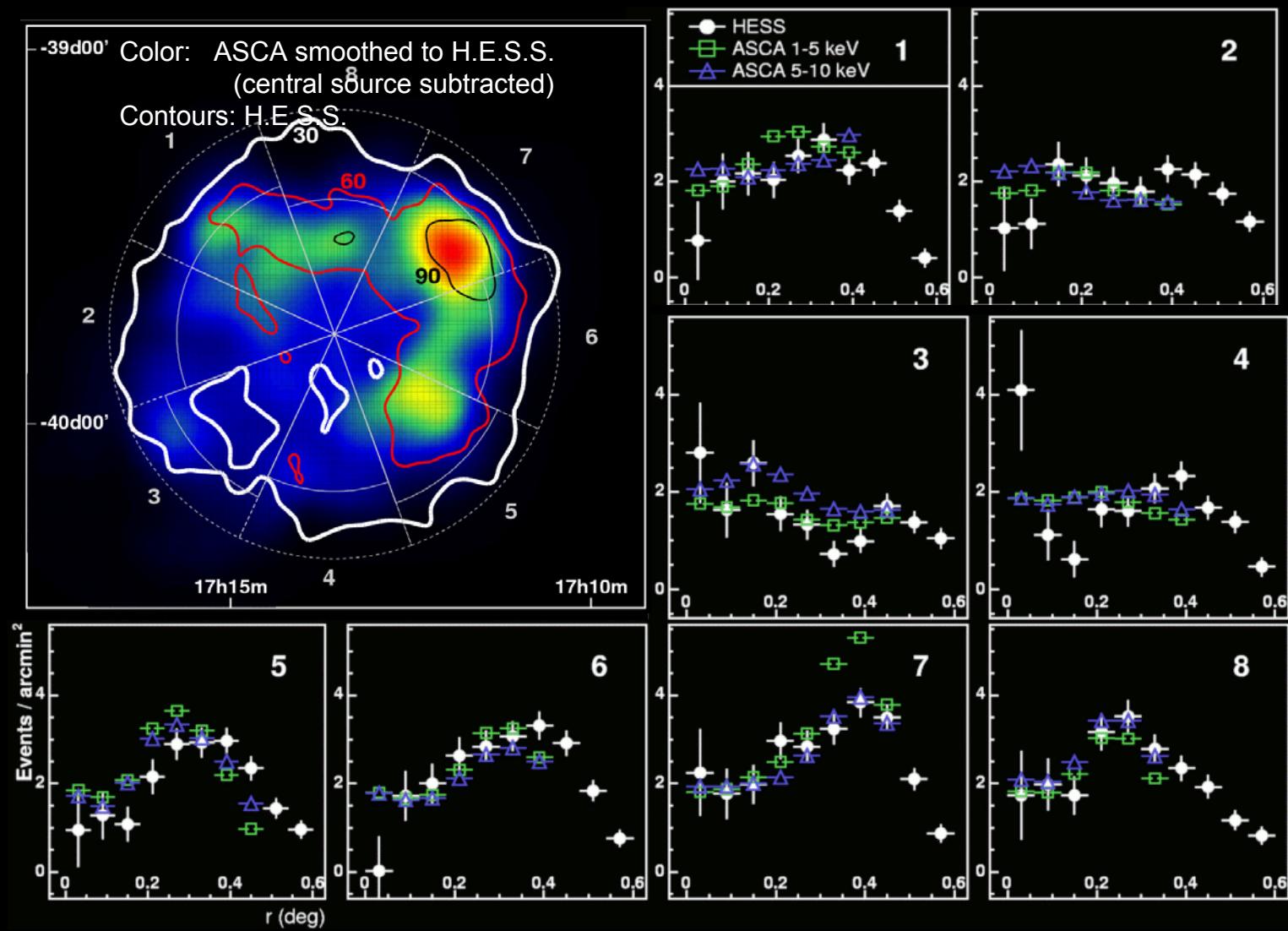
Flux vs. photon index



TeV spectral shape does not change across the SNR

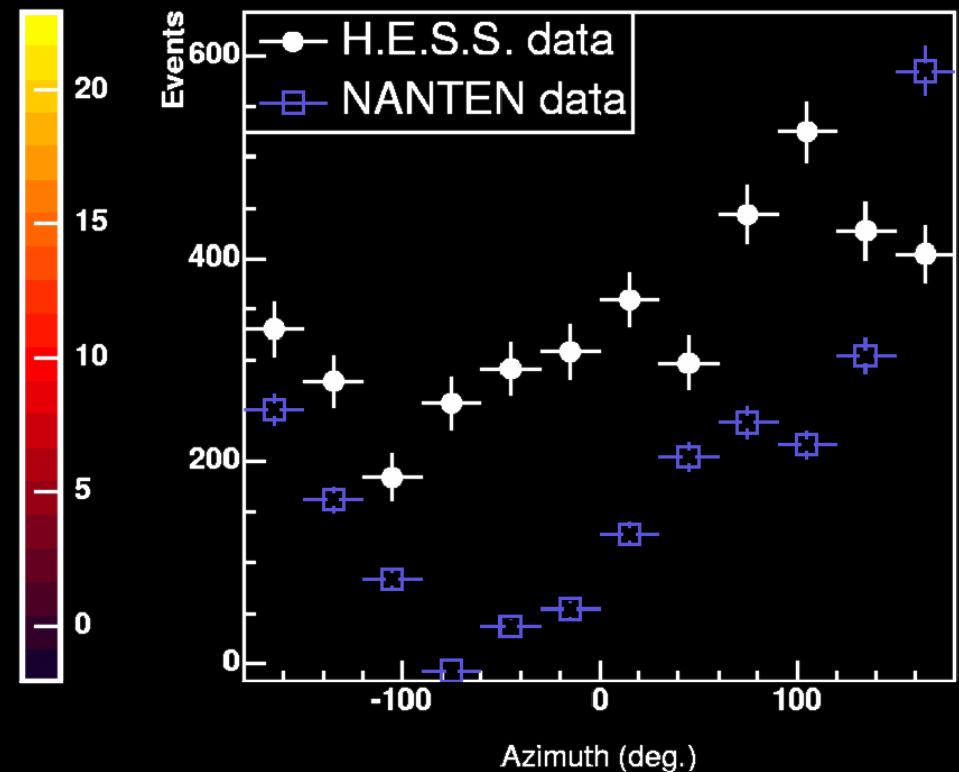
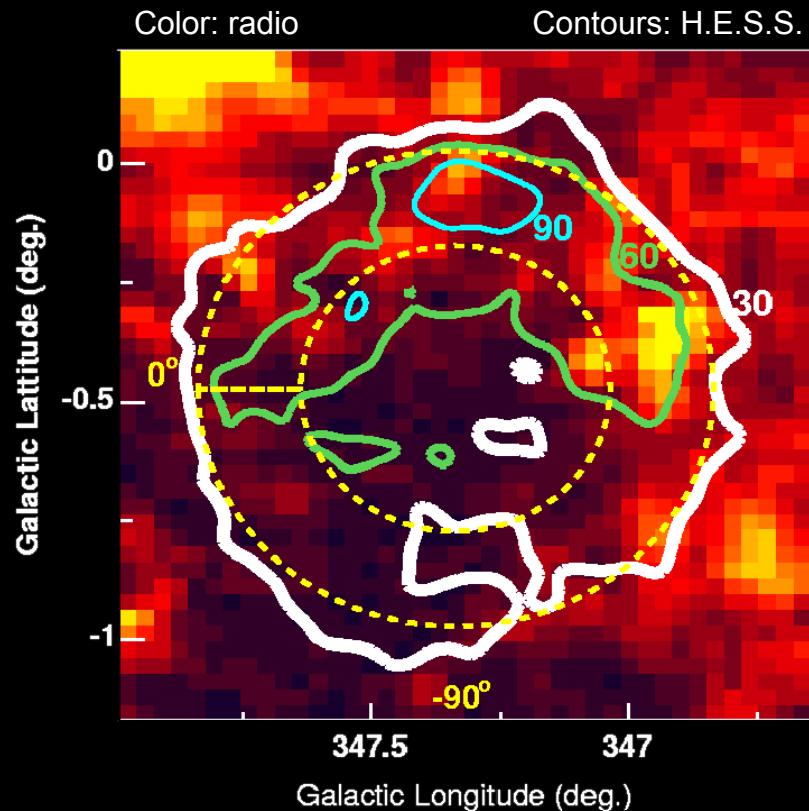


RX J1713: TeV - X-Ray Correlation





RX J1713: Correlation TeV - CO Data ?



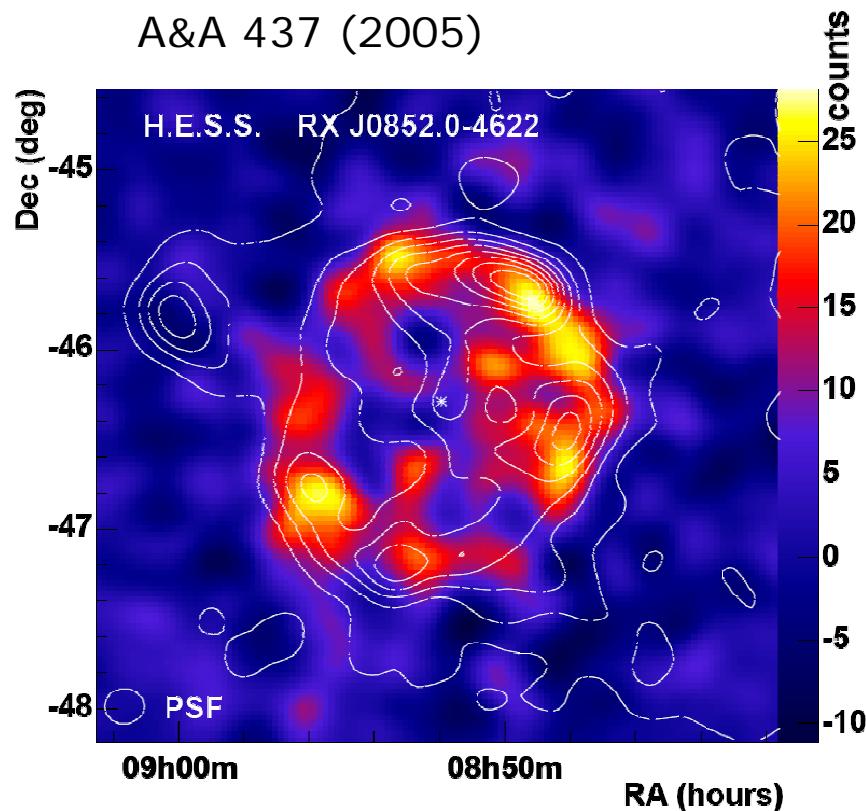
Nanten CO – data @
-11 km/sec ... -3 km/sec
(0.4 1.5 kpc)

No good correlation between
gas density and TeV emission

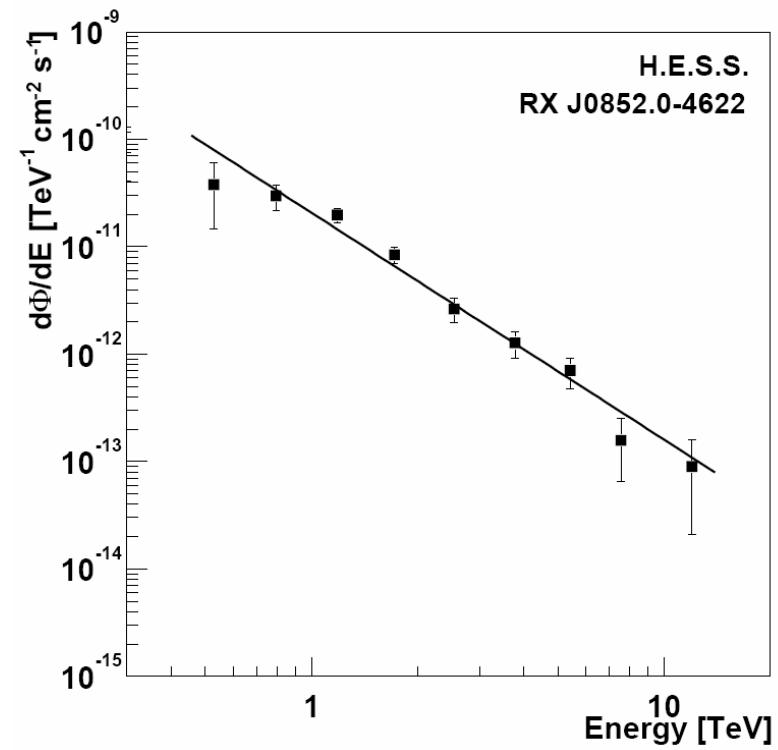


RX J0852.0-4622: "Vela Junior"

A&A 437 (2005)



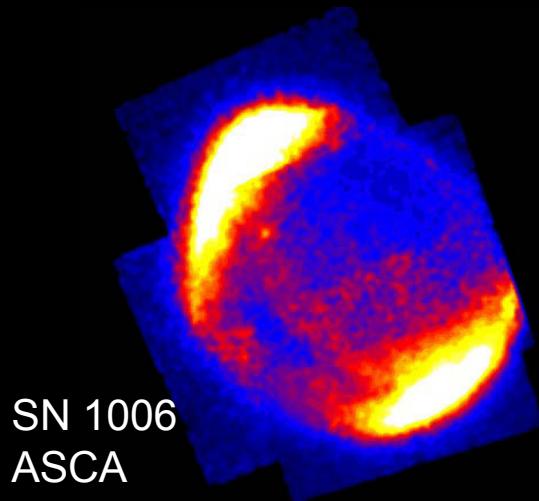
3.2 h of data (no patience)
700 gammas
 12σ , ~ 2 deg diameter



Spectral index 2.1
Crab-like flux



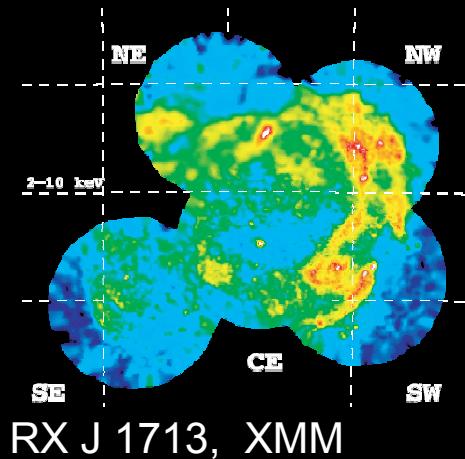
SNRs in the Light of TeV γ -Rays (>2004)



SN 1006
ASCA



Cassiopeia A
Chandra

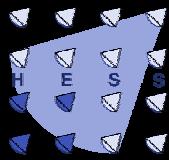


RX J 1713, XMM

Supernova	d [kpc]	Flux [Crab Units]	Exp.
SN 1006	1.4 – 2.1	0.5	CANGAROO
RX J1713.7...	1 – 6	0.7	CANGAROO
Cassiopeia A	3.3 – 3.7	0.03	HEGRA
RX J 0852.0	0.2 – 0.5	~1	HESS

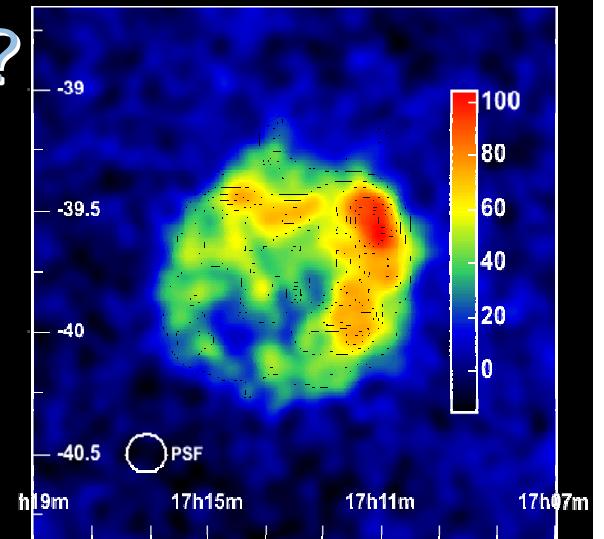
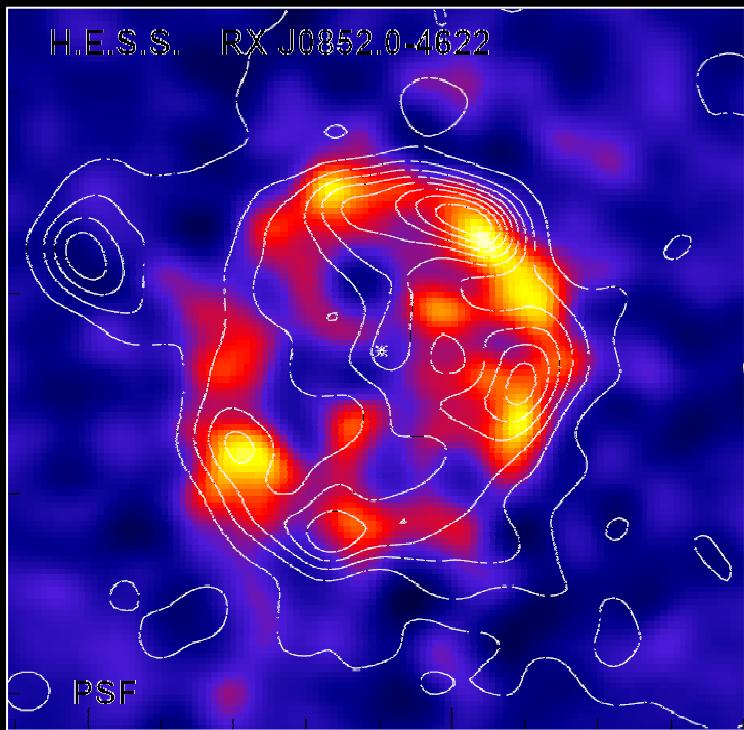


HESS J1640, HESS J1808, HESS J1813, HESS J1834, ...



Found *the* CR accelerators ?

Proven that
SNR shock waves are cosmic accelerators
up to energies of $O(100 \text{ TeV})$



What is the efficiency of energy conversion from SNR explosion into CR (distance ?, gas density ?) ?

- Large lever arm from GeV to ~100 TeV ...
- Further multi- λ studies needed ...
- More sources ...
- And maybe neutrinos ...

Searching for the Cosmic Particle Accelerators

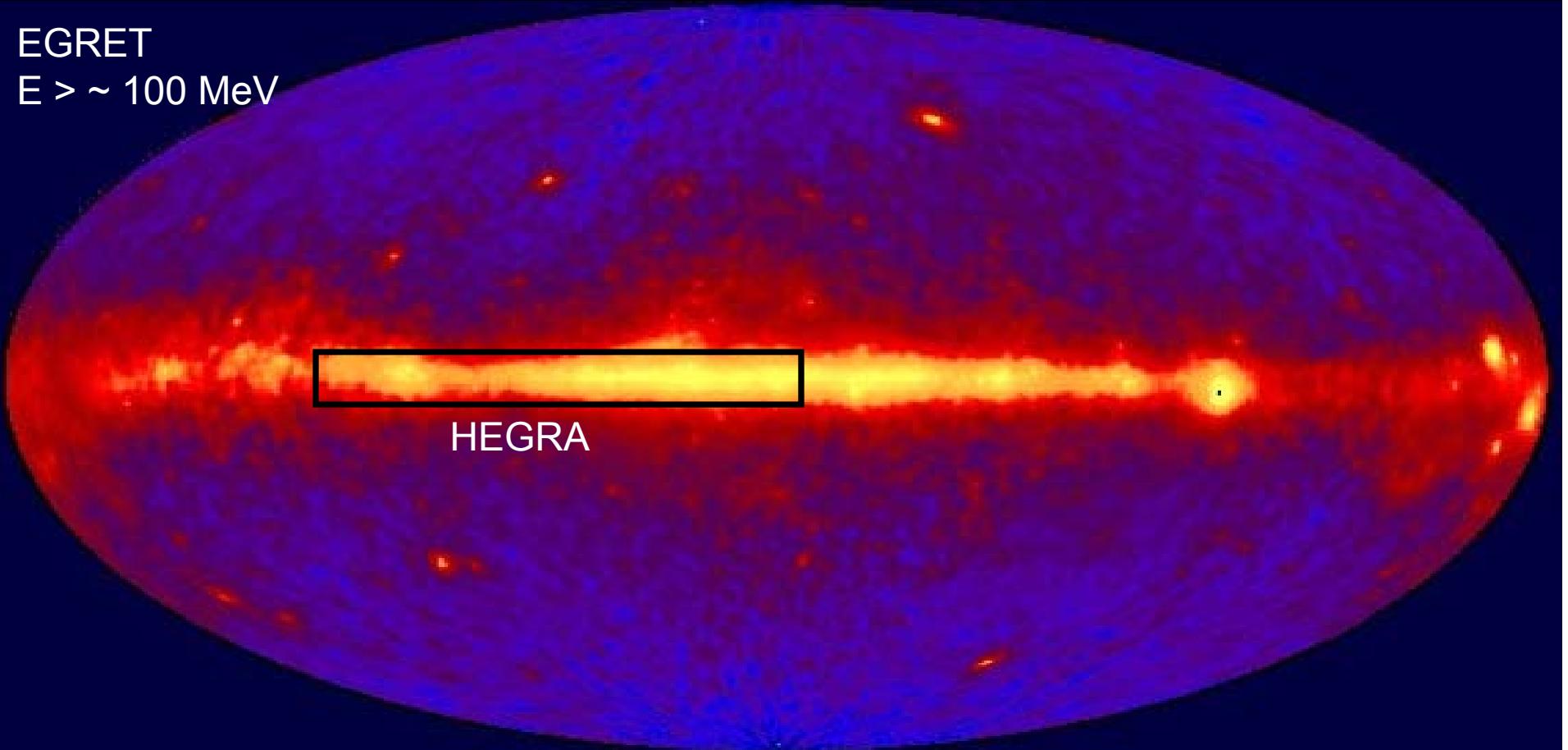
- TeV Source Statistics
- Supernova Remnants
- The Galactic Plane
- Galactic Center Region
- The Extragalactic BG Light



Survey of the Galactic Plane

EGRET

$E > \sim 100$ MeV



So far, only pointed observations

Galactic plane full of interesting objects (SNR, Pulsars, PWN, ...)

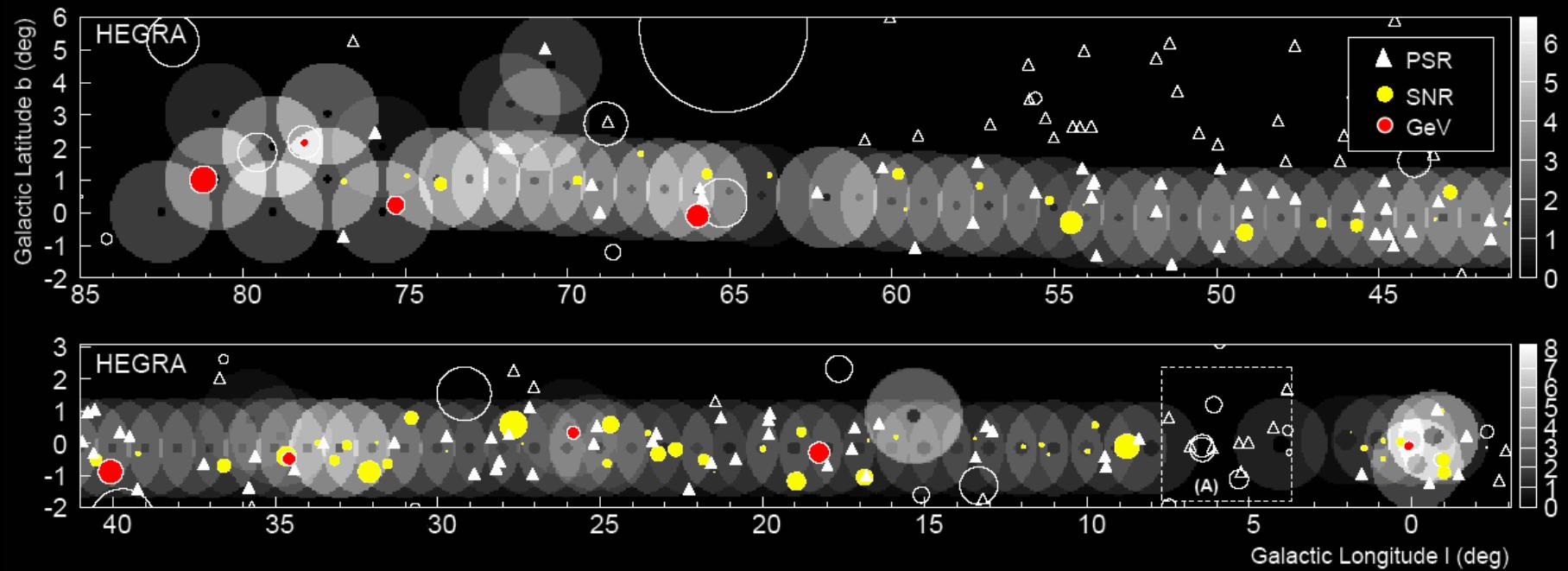
+ interaction of Cosmic Rays with interstellar medium

→ how does the Galactic plane look like at TeV energies ?

The HEGRA Survey of the Galactic Plane

170 h in 1997/1998

Small FoV Instruments: → Scan



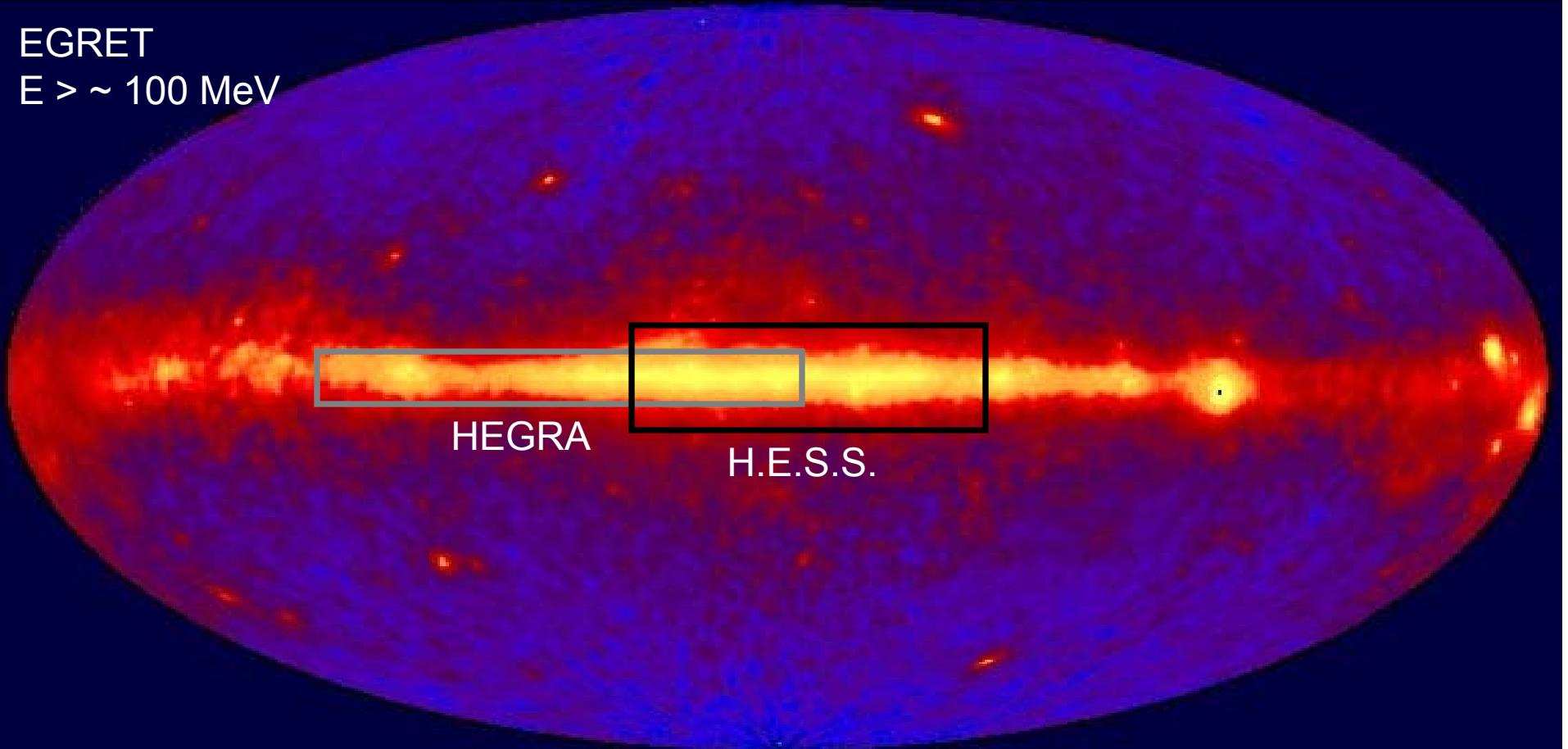
HEGRA Gal. Plane survey
90° x 3° @ 0.1 – 0.5 Crab U.L.
Limits on 63 SNR
86 pulsars
9 GeV sources

Large FoV Instruments:
...

Survey of the Galactic Plane

EGRET

$E > \sim 100$ MeV



So far, only pointed observations shown

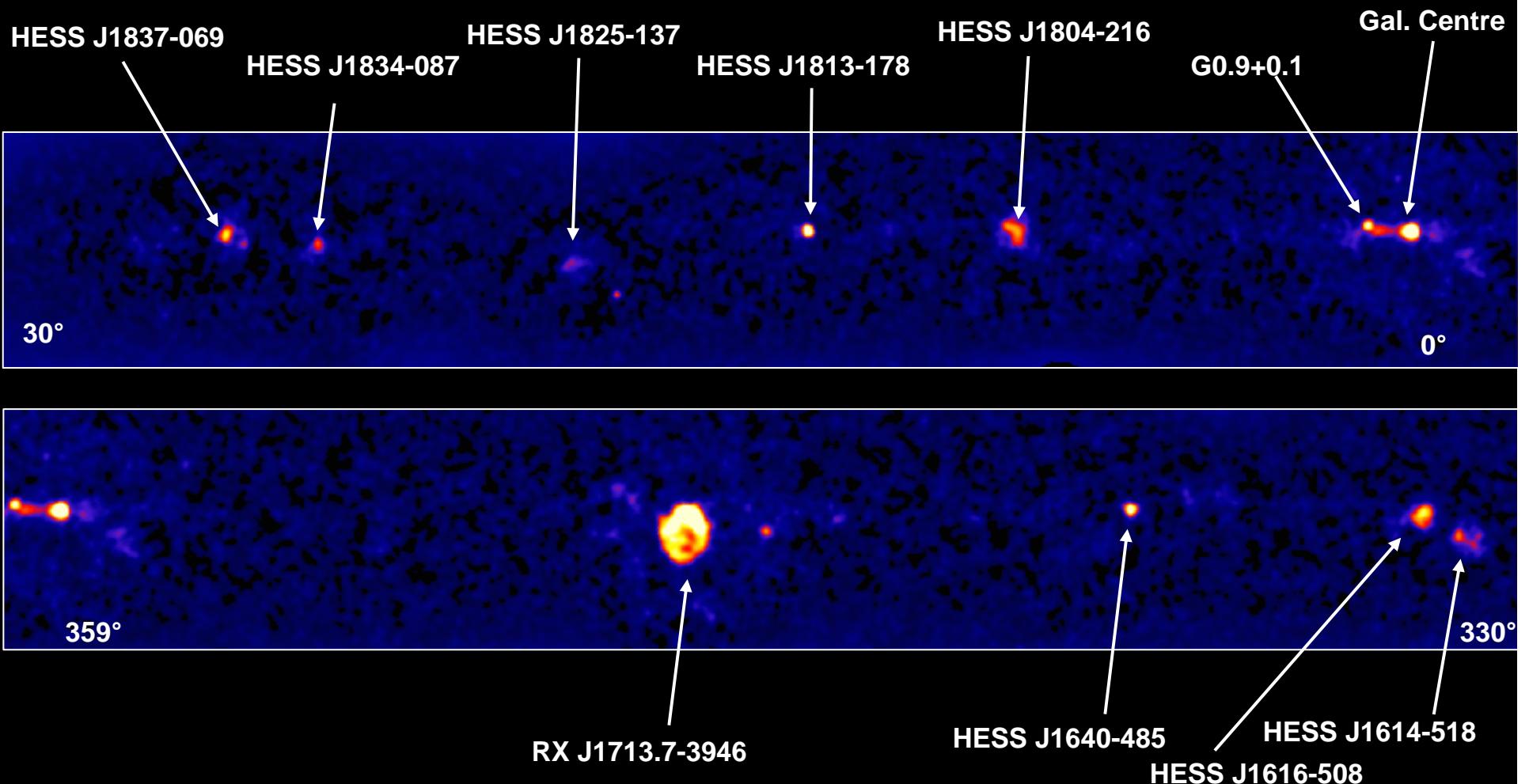
Galactic plane full of interesting objects (SNR, Pulsars, PWN, ...)

+ interaction of Cosmic Rays with interstellar medium

→ How does the Galactic plane look like at TeV energies ?



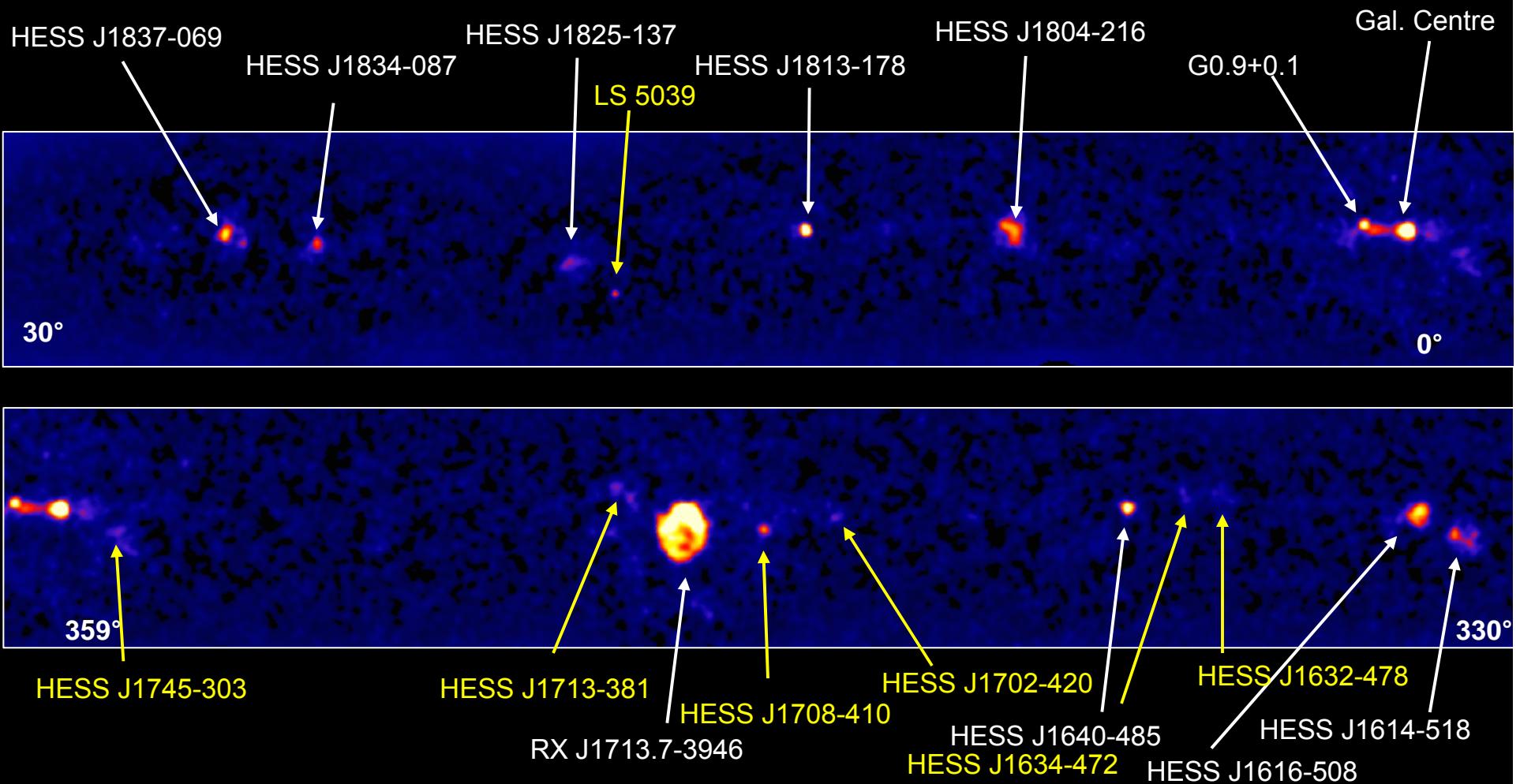
The H.E.S.S. Survey Galactic Plane



230 h in 2004, 500 pointings; sensitivity 2% of Crab above 200 GeV
8 new sources @ $> 6 \sigma$ post-trial (+3 known)



The H.E.S.S. Survey Galactic Plane



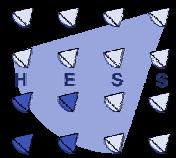
230 h in 2004

8 new sources @ $> 6 \sigma$ post-trial (+3 known)

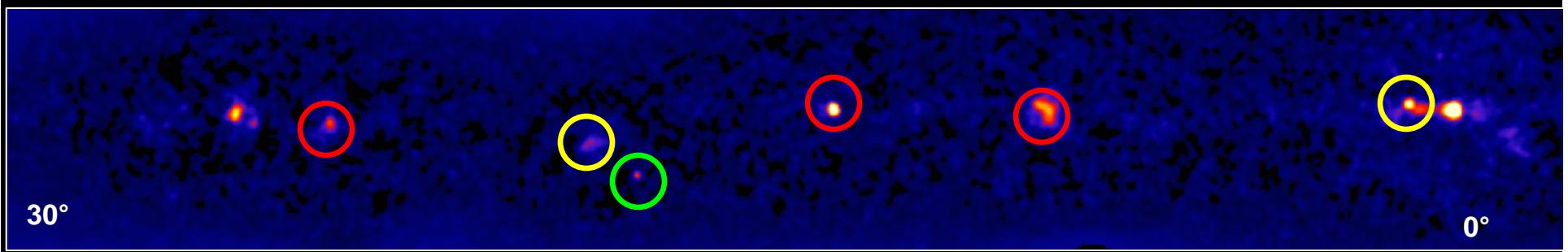
6 new sources @ $> 4 \sigma$ post-trial

Aharonian et al, Science (2005)

Aharonian et al, ApJ (2006)

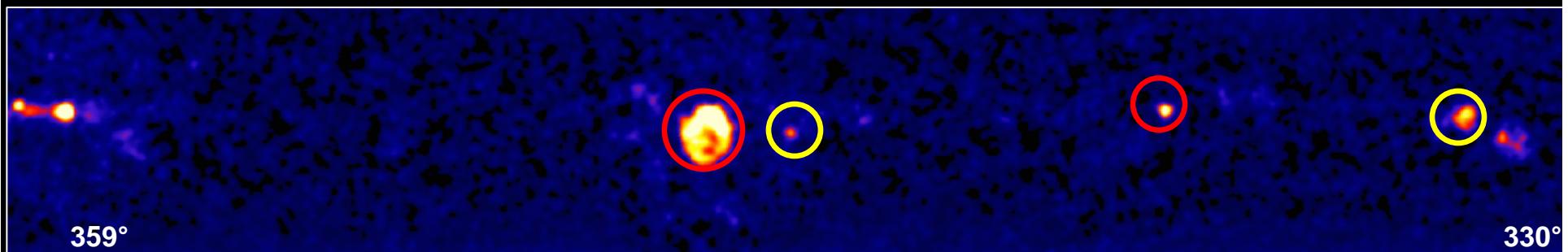


Classes of Objects / Possible Counterparts



30°

0°



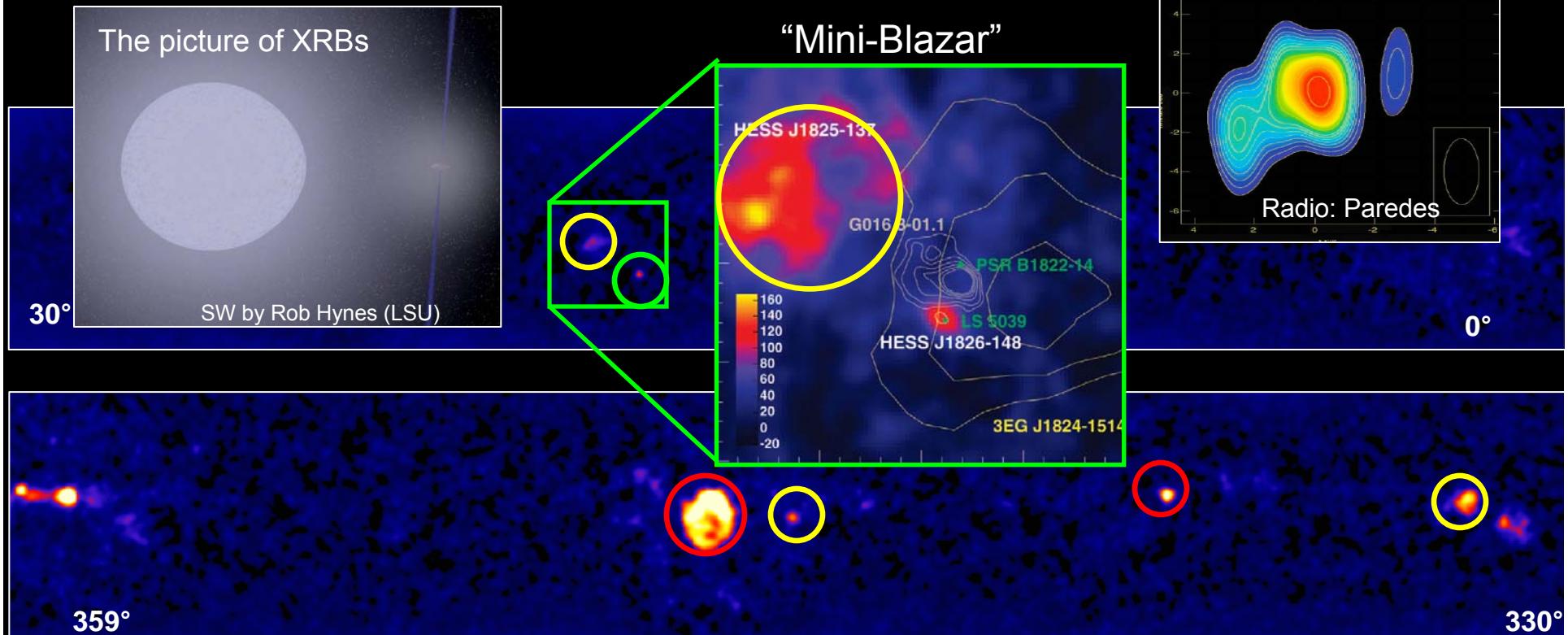
359°

330°

- SNR
- PWN
- X-ray binary



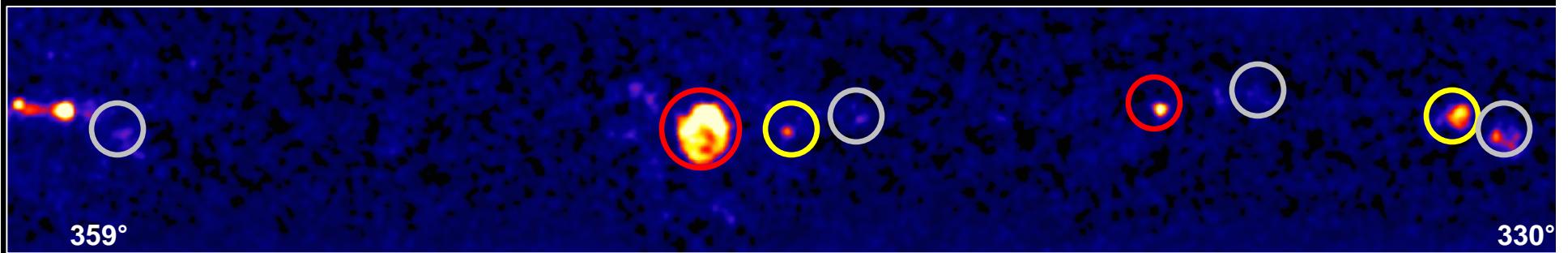
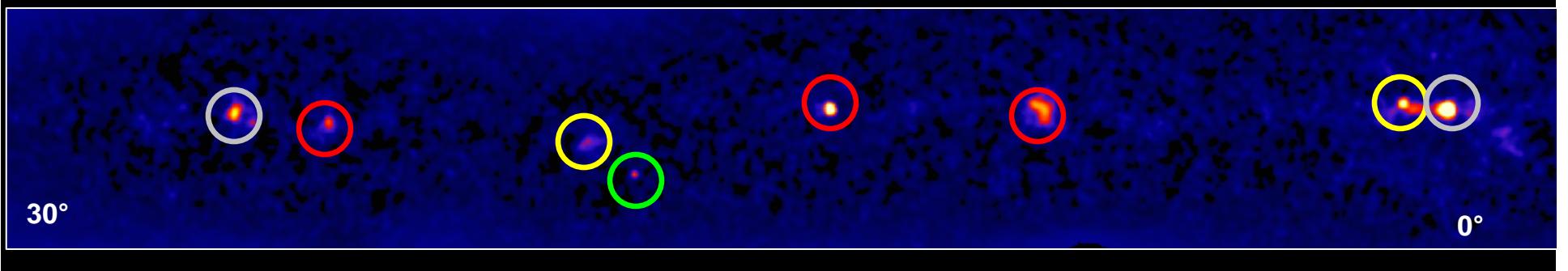
Counterparts: X-ray Binary LS5039



Aharonian et al, Science (2005)



Classes of Objects / Counterparts



SNR
 PWN
 X-ray binary

unkown

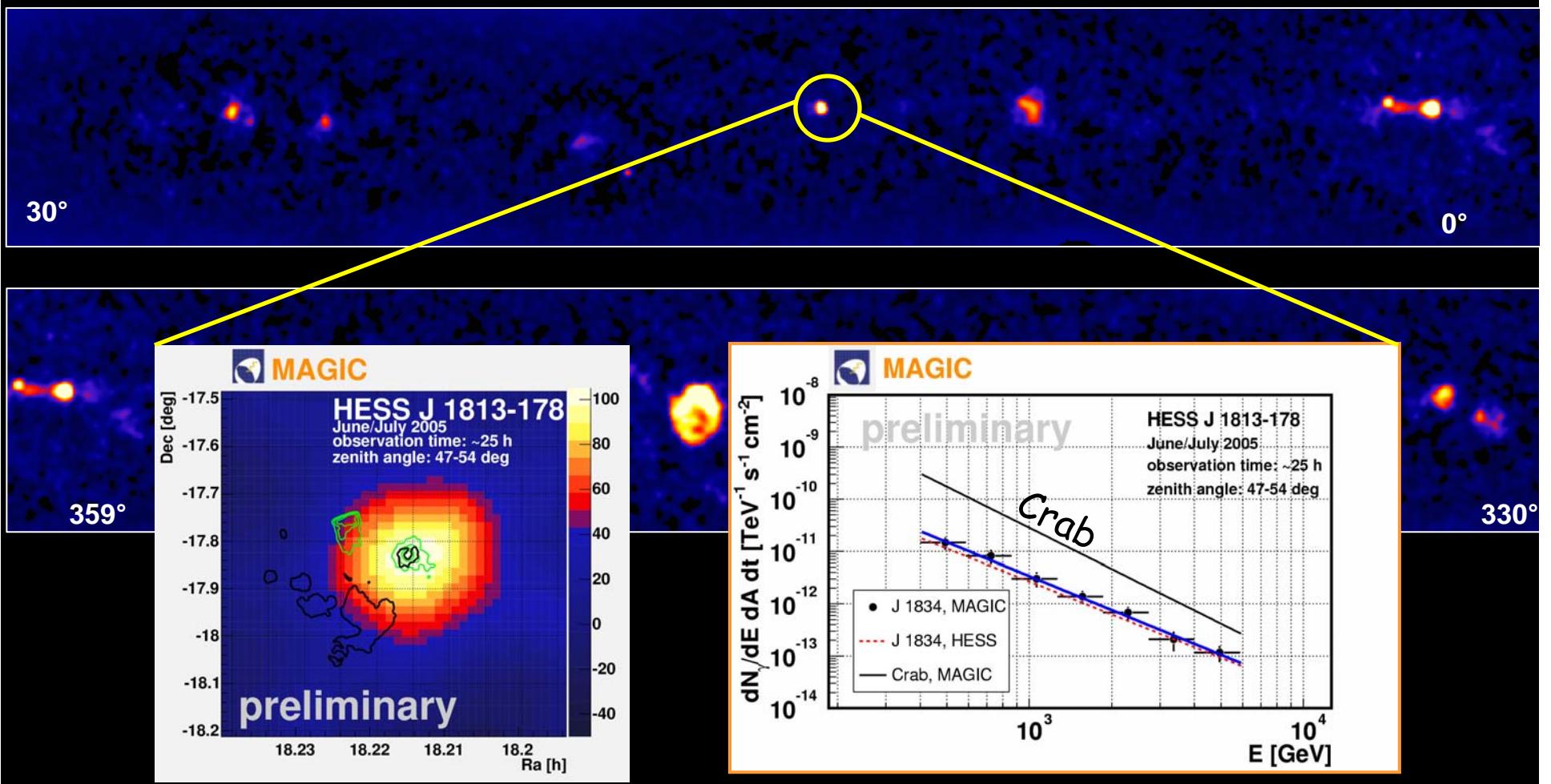
Need more multi- λ coverage

At least 3 objects in the scan
with no counterpart
like
→ TeV J2032-4130 by HEGRA
→ HESS J1303-631



Confirmation of H.E.S.S. Sources

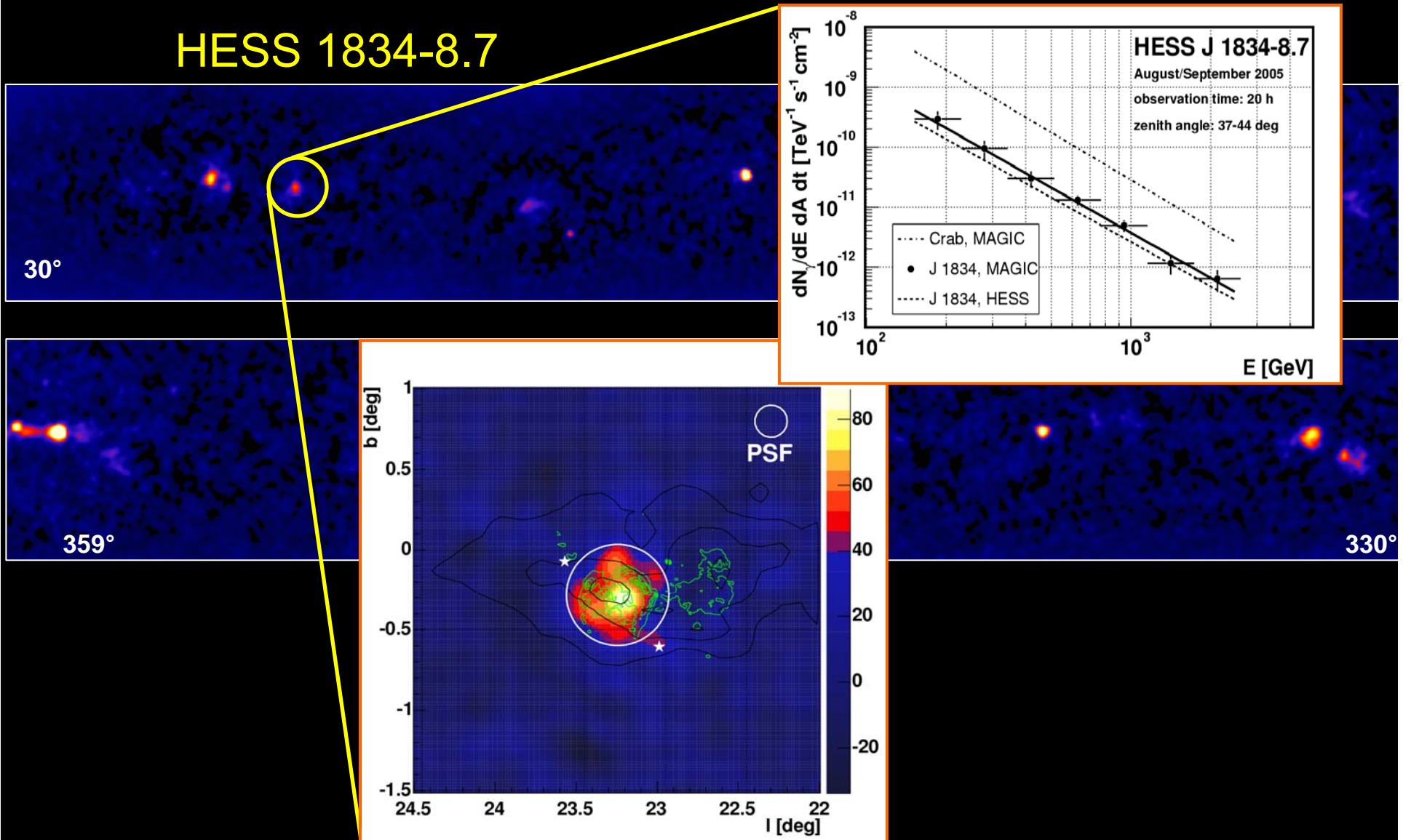
HESS J1813-178





Confirmation of H.E.S.S. Sources

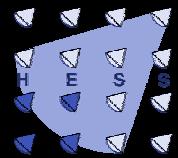
HESS 1834-8.7



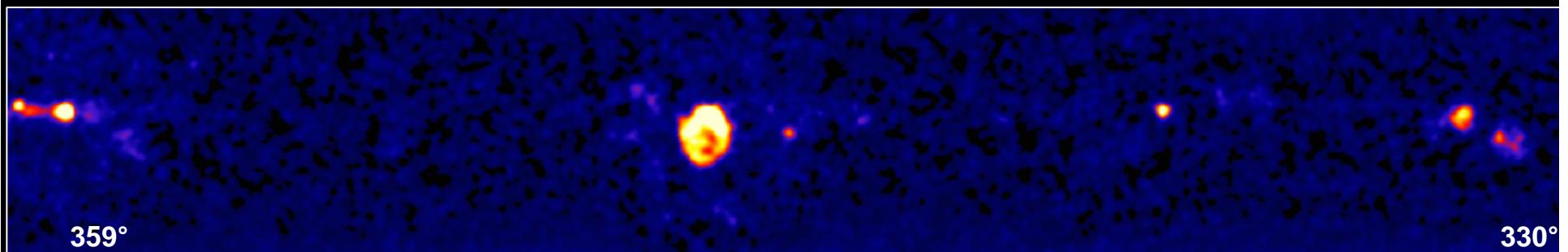
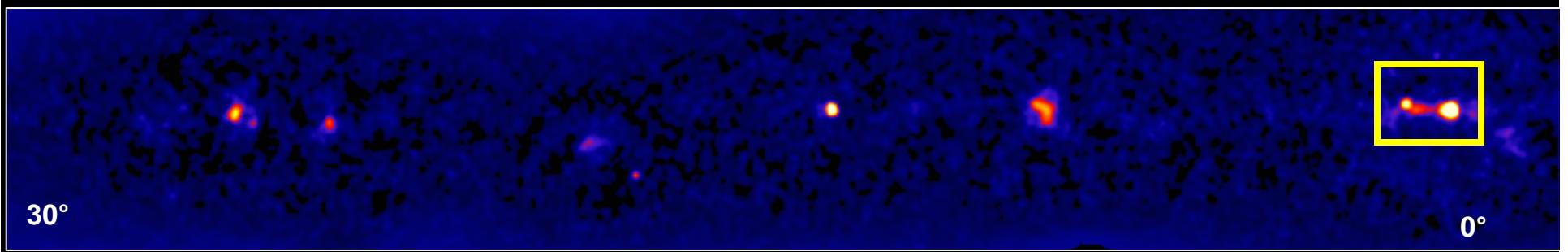
Searching for the Cosmic Particle Accelerators

- TeV Source Statistics
- Supernova Remnants
- The Galactic Plane
- Galactic Center Region
- The Extragalactic BG Light





The Center of our Galaxy



The Galactic Center Region

Why is it interesting ?

Astrophysics:

full “zoo” of objects

Pulsars and PWN

Supernova remnants

X-Ray binaries

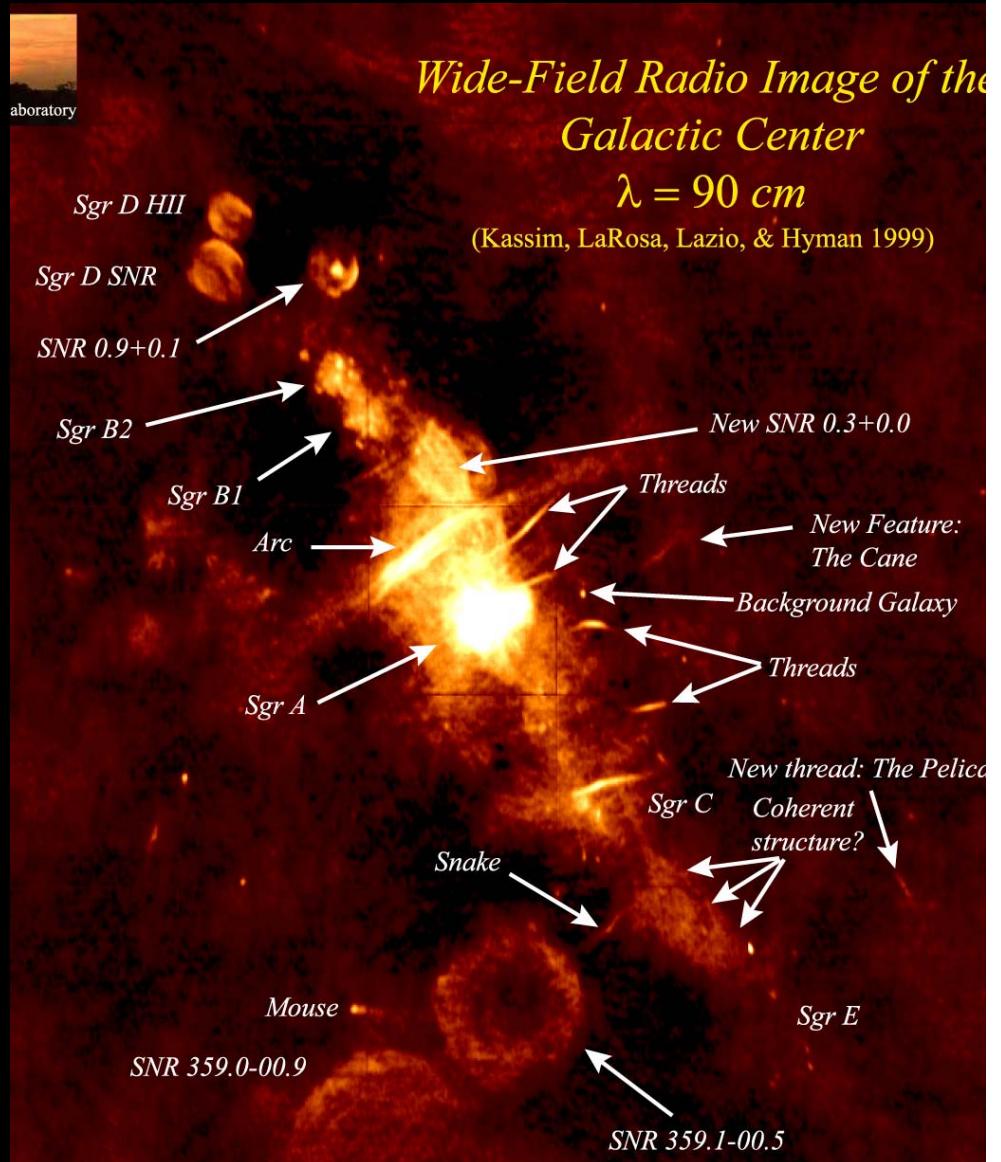
Molecular clouds

Bit more exotic:

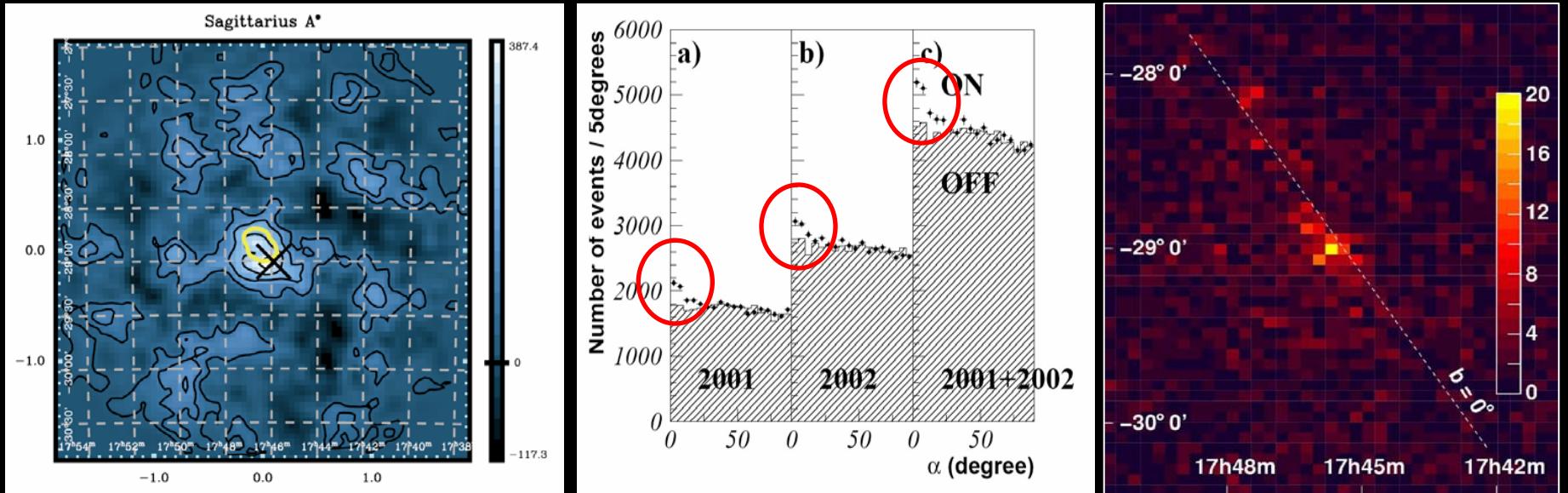
Supermassive BH Sgr A*

Even more exotic:

Dark Matter accumulation
→ Neutralino annihilation



TeV Gamma-Rays from the Galactic Center



Whipple

Kosack et al

- 26 h in 8 years
- 2.8 TeV Threshold
- 3.7 sigma

CANGAROO II

Tsuchiya et al

- 67 h in 2 years
- 250 GeV Threshold
- ~10 sigma

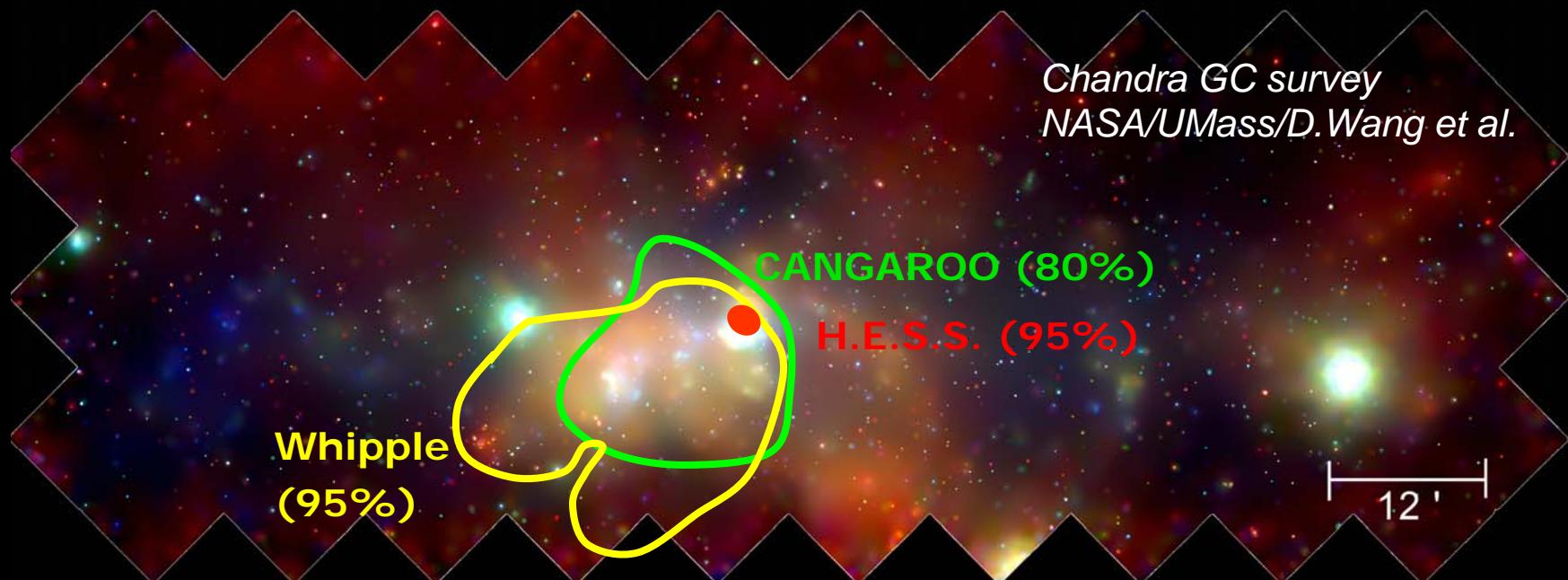
H.E.S.S.

Aharonian et al

- 17 h (2 tel., 2003 data)
- 160 GeV Threshold
- 11 sigma

2004: 3 groups claim detection

TeV Gamma-Rays from the Galactic Center

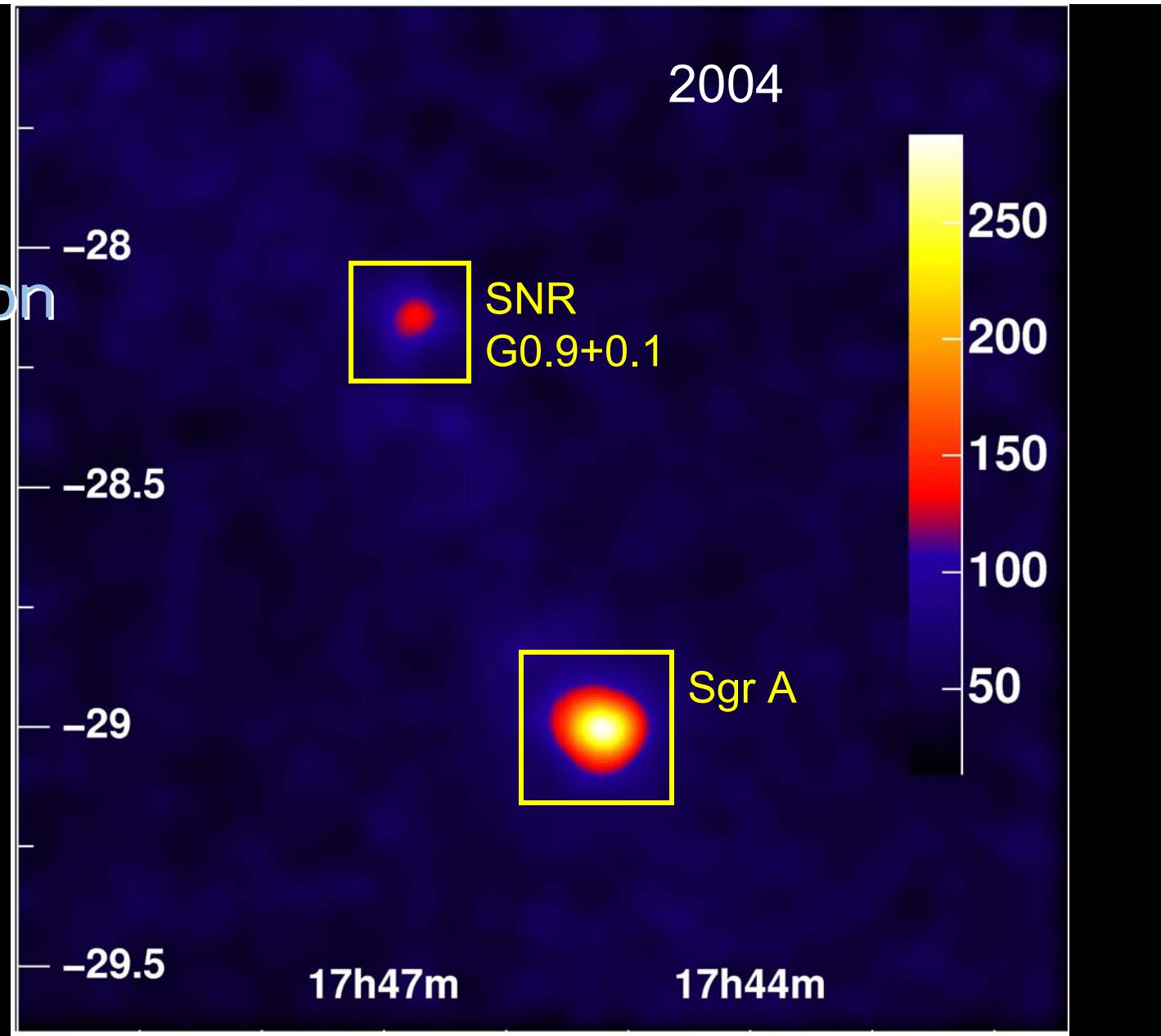


Contours from Hooper et al. 2004

*Chandra GC survey
NASA/UMass/D.Wang et al.*

The Galactic Center Region

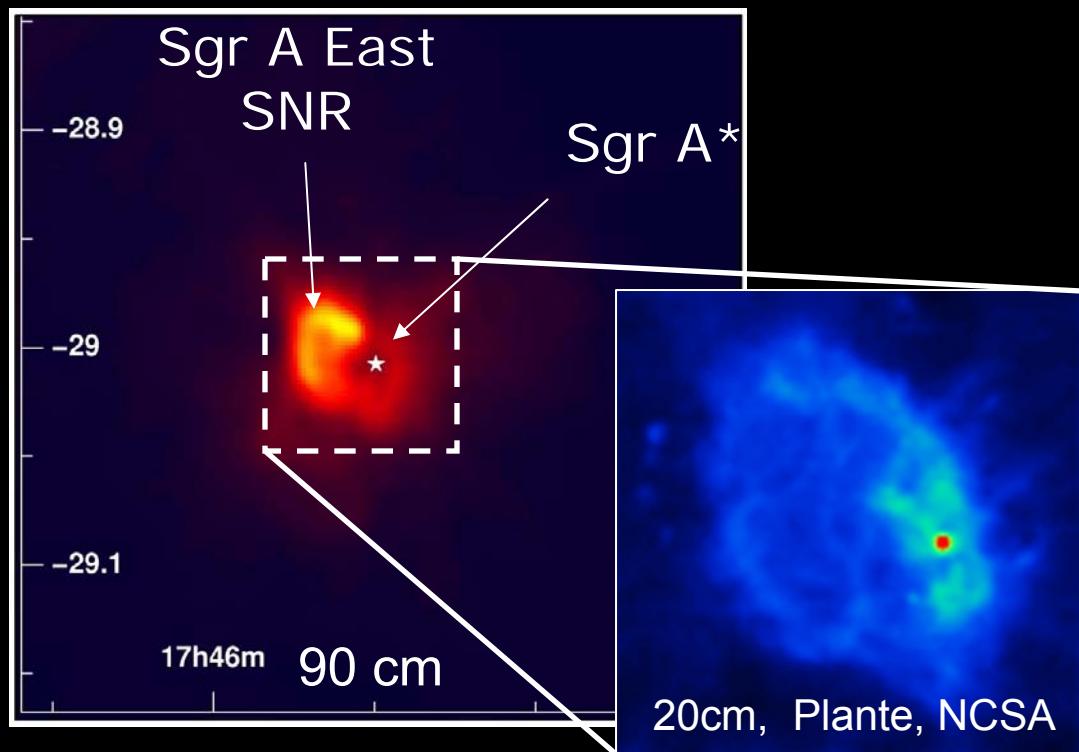
38 σ in ~49 h
~1860 events
Flux:
~5 % of Crab



Gamma-Rays from Sgr A East or Sgr A* ?

Sgr A*

- Fast rotating 3×10^6 SM black hole in external magn. field
 - could accelerate protons to 10^{18} eV (synchrotron or $\pi^0 \rightarrow \gamma\gamma$)
 - or accelerate electrons (γ -rays via IC)
- Or acceleration at shocks in the accretion disk



Sgr A East

10000 yr old SNR

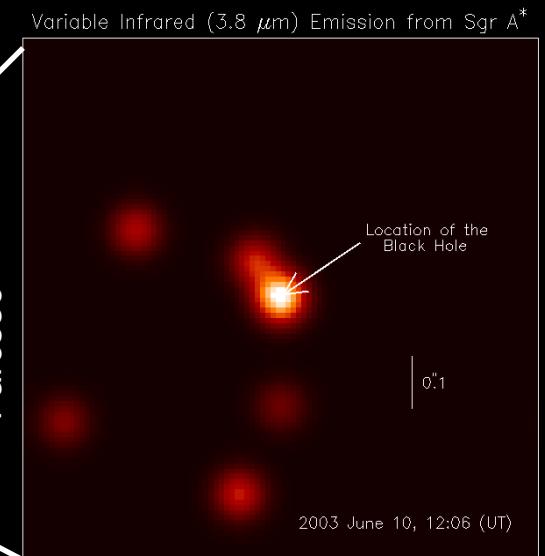
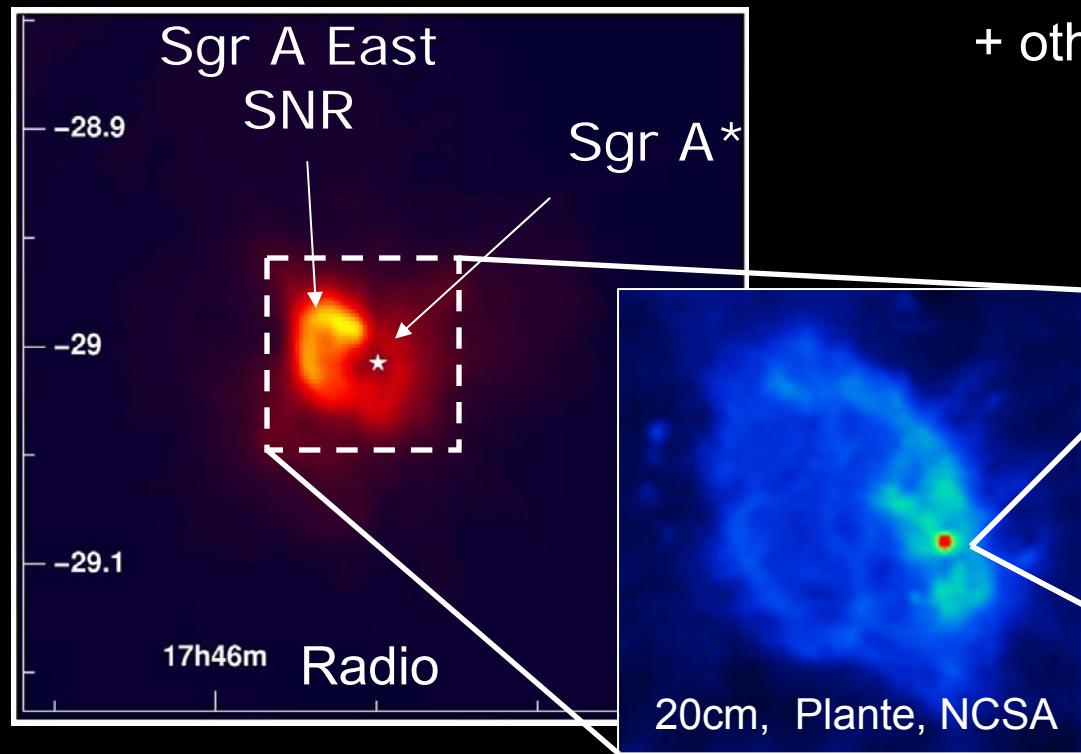
- Surrounds (partly) Sgr A*
- Shock acceleration in blast wave.
→ Material for accretion on BH

Sgr A East or *Sgr A** or ... ?

Observables:

- Position (extension) of emission
- Energy spectrum and range
- Variability / periodicity

+ other wavelengths



Ghez et al (2004)



TeV Source Position

Consistent with point-like emission

Distance to Sgr A* :

$3'' \pm 12''_{\text{stat}} \pm 28''_{\text{sys}}$

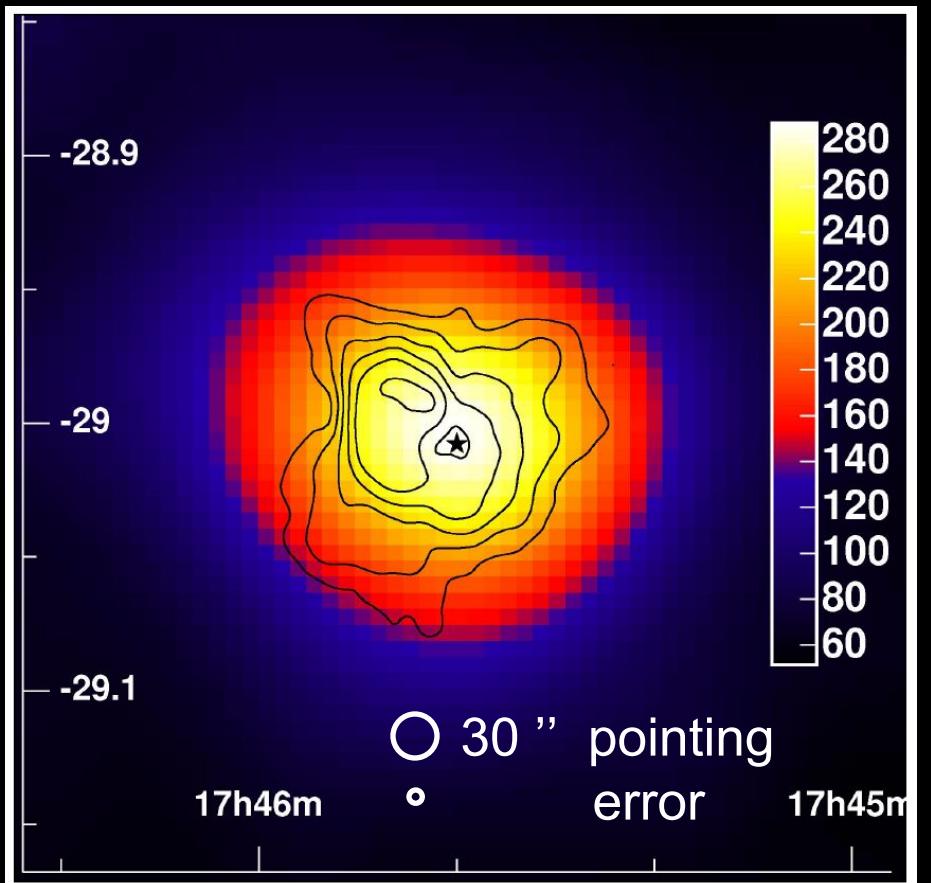
Could be Sgr A* or Sgr A East

→ call it:

HESS J1745-290 ...

... and improve pointing
to $< 10''$

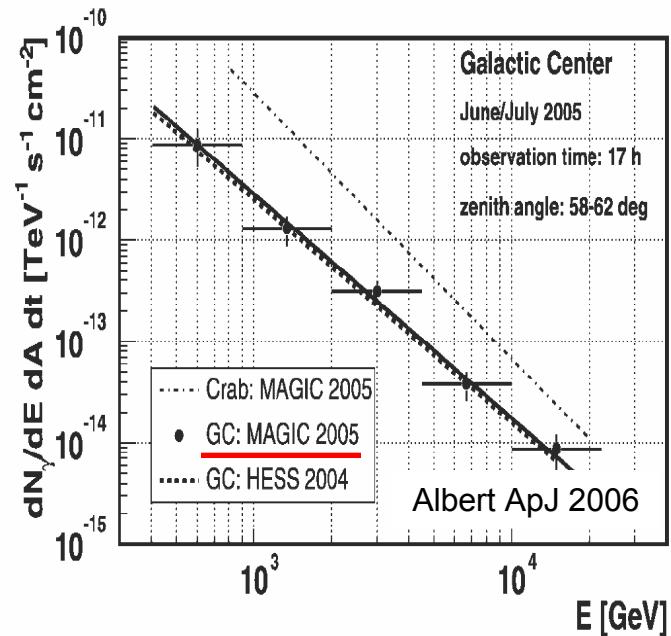
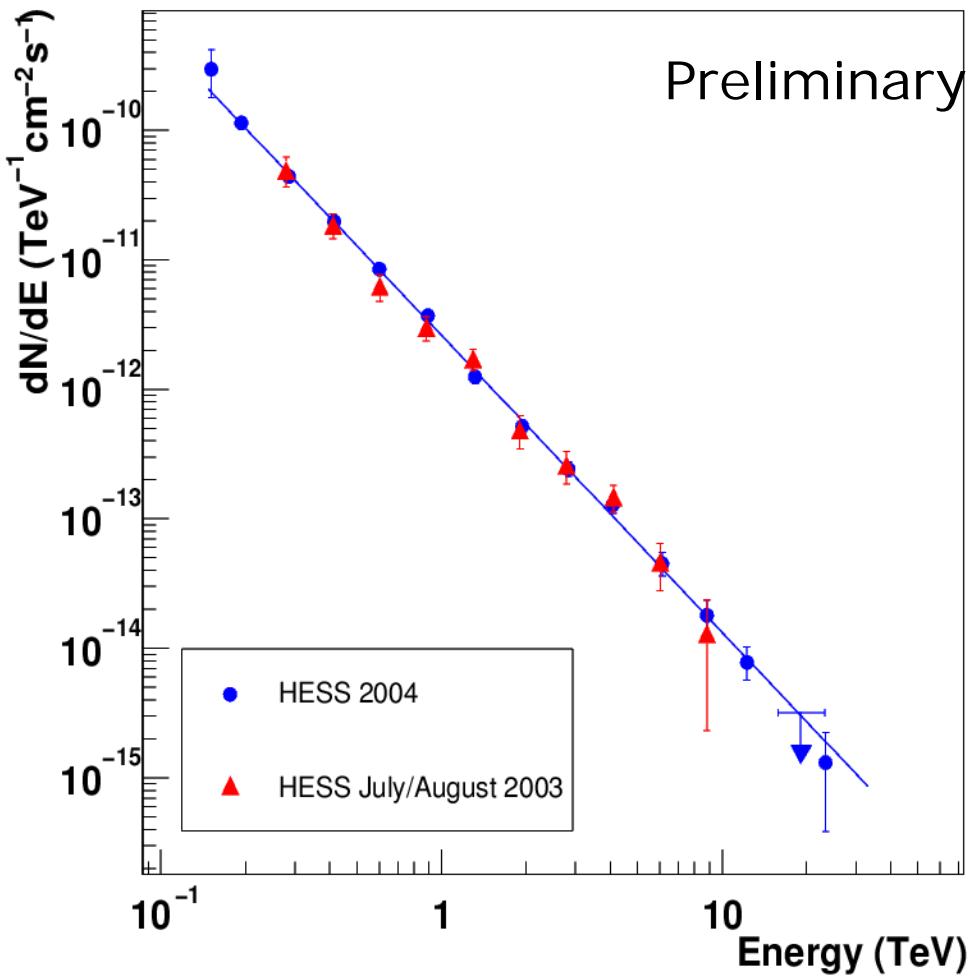
Contour: Sgr A East (radio)
Color: H.E.S.S. (Gev-TeV)



TeV H.E.S.S.



Galactic Center: Energy Spectrum



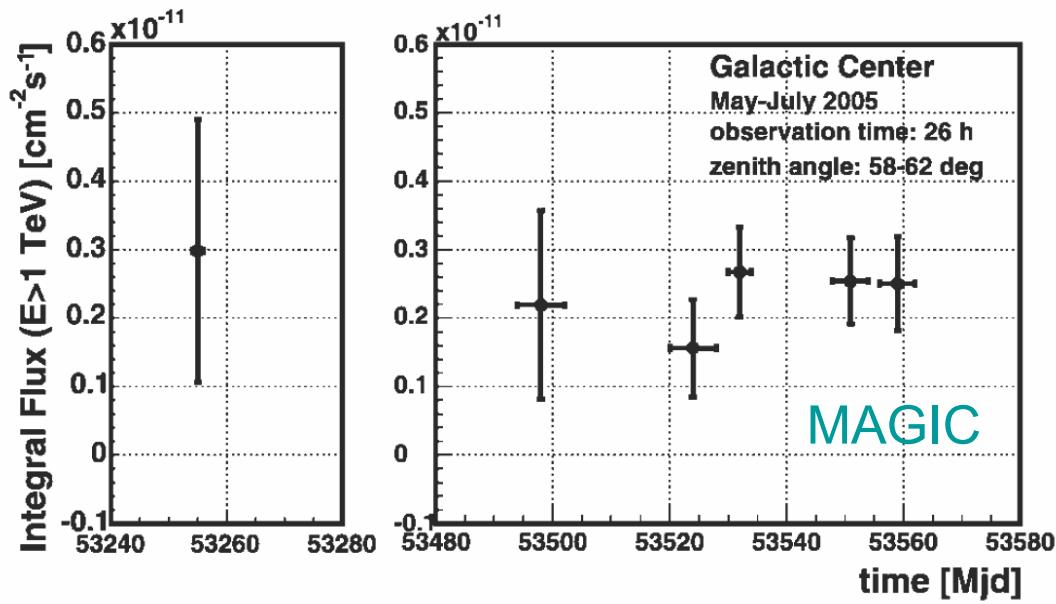
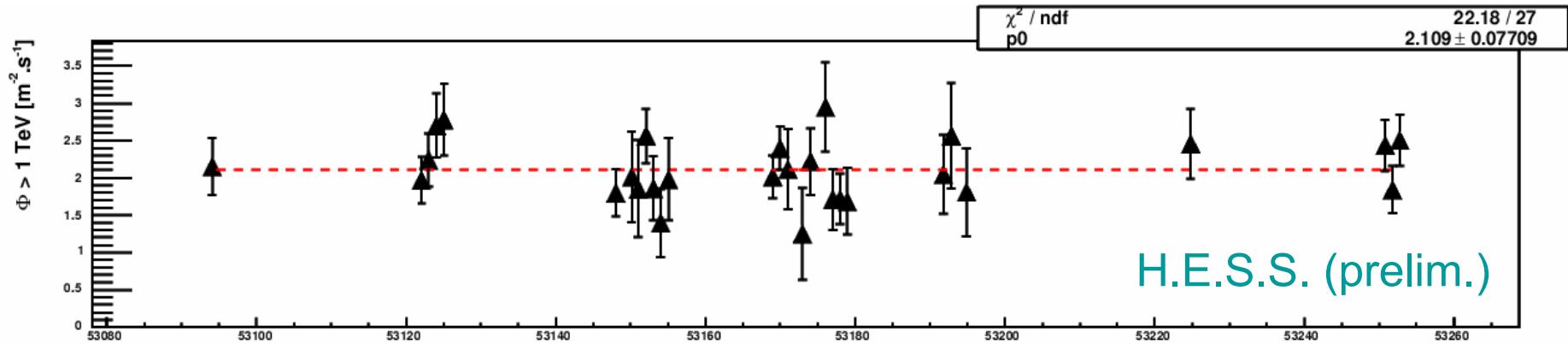
Flux: $\sim 5\%$ of Crab ($E > 165$ GeV)

Power law
with photon index

$$\Gamma = 2.3 \pm 0.04 \text{ (stat)} \pm 0.1 \text{ (sys)}$$



Galactic Center: Variability ?



No significant variability

- on year scale
- on month scale
- on day scale
- on hour scale

So far no big X-ray flare contemporaneous with TeV observations

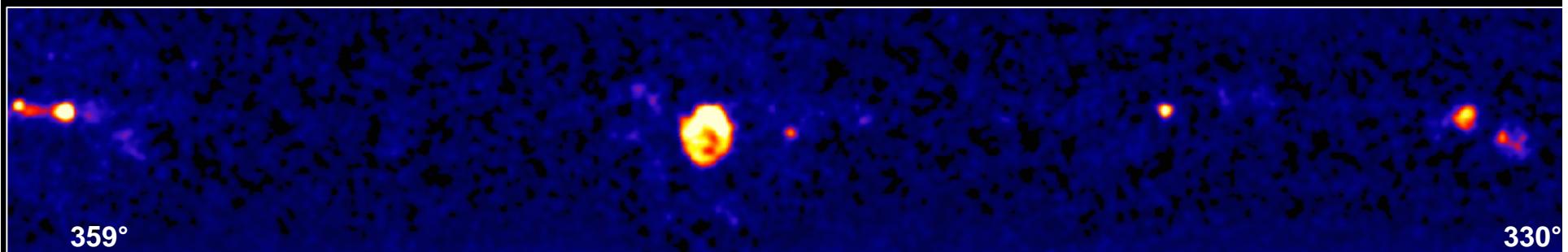
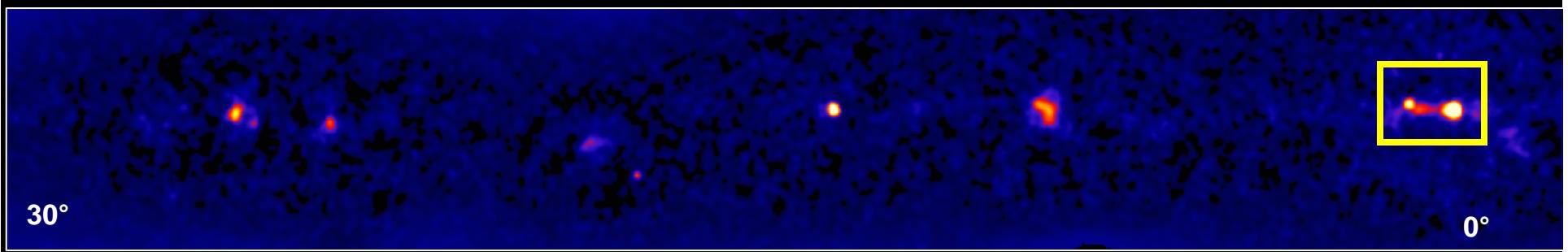
Searching for the Cosmic Particle Accelerators

- TeV Source Statistics
- Supernova Remnants
- The Galactic Plane
- **Galactic Center Region (diffuse)**
- The Extragalactic BG Light





GC Region: Diffuse Emission

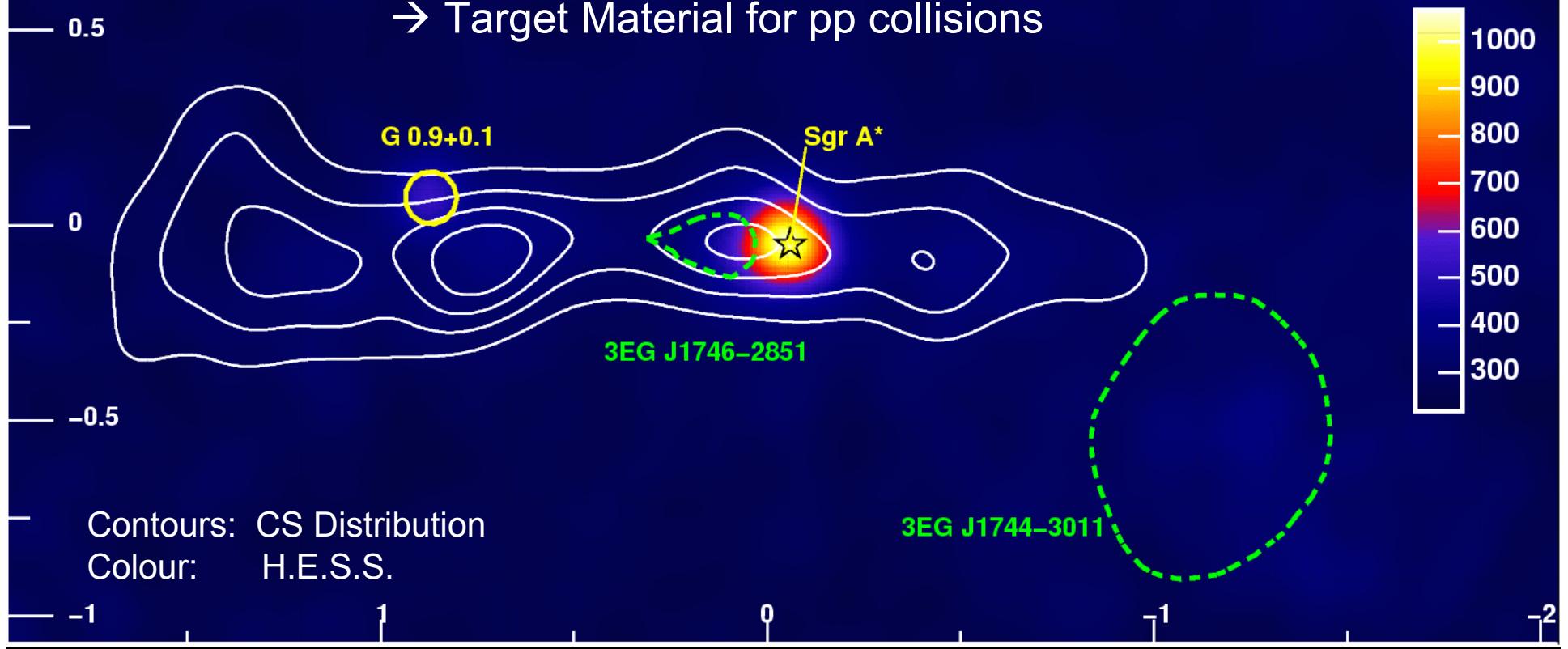




Diffuse Emission in the GC Region

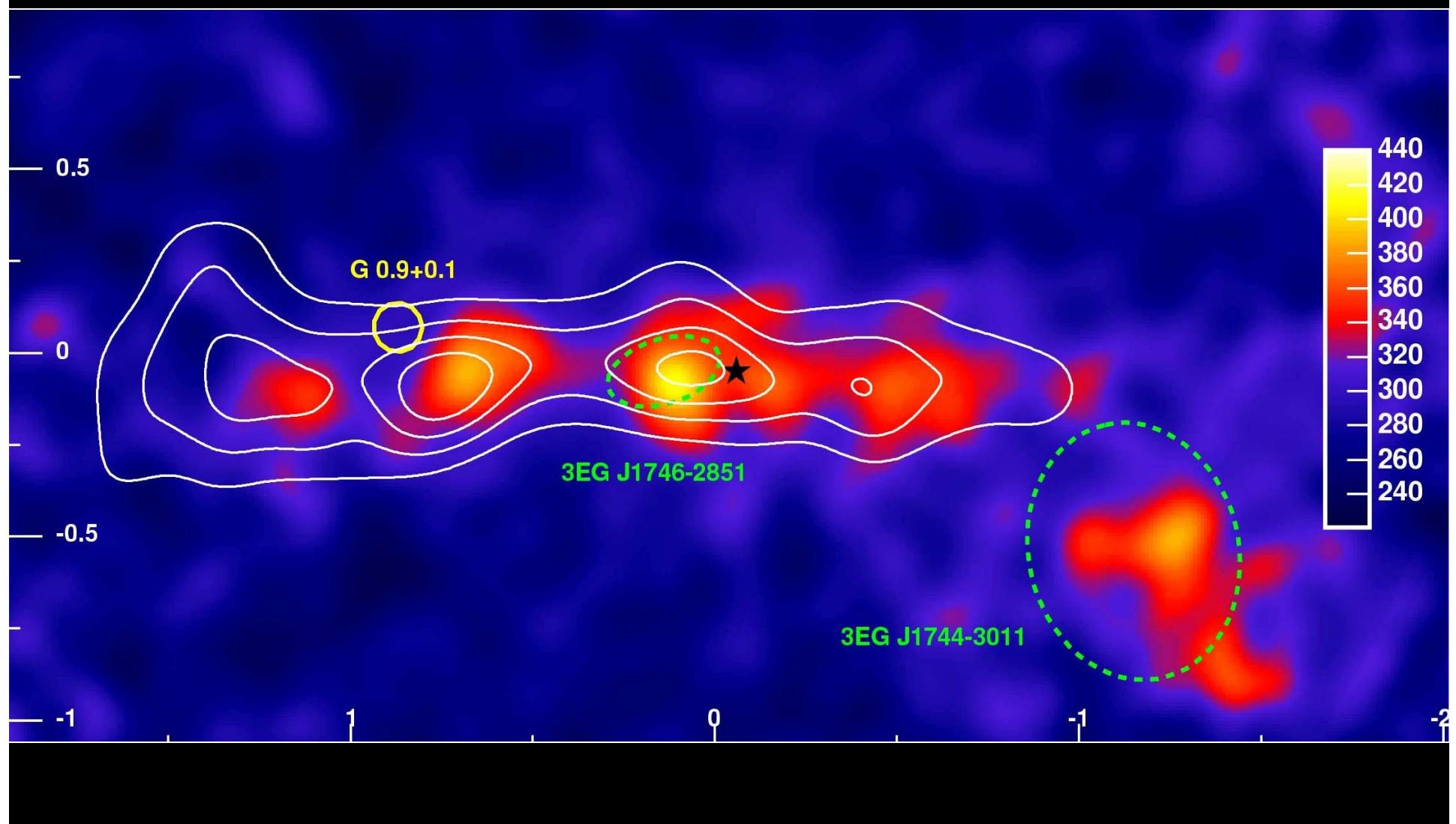
Molecular Clouds with mass of $3\text{--}6 \cdot 10^7 M_{\text{Sun}}$

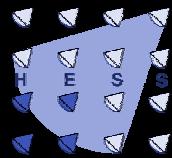
→ Target Material for pp collisions



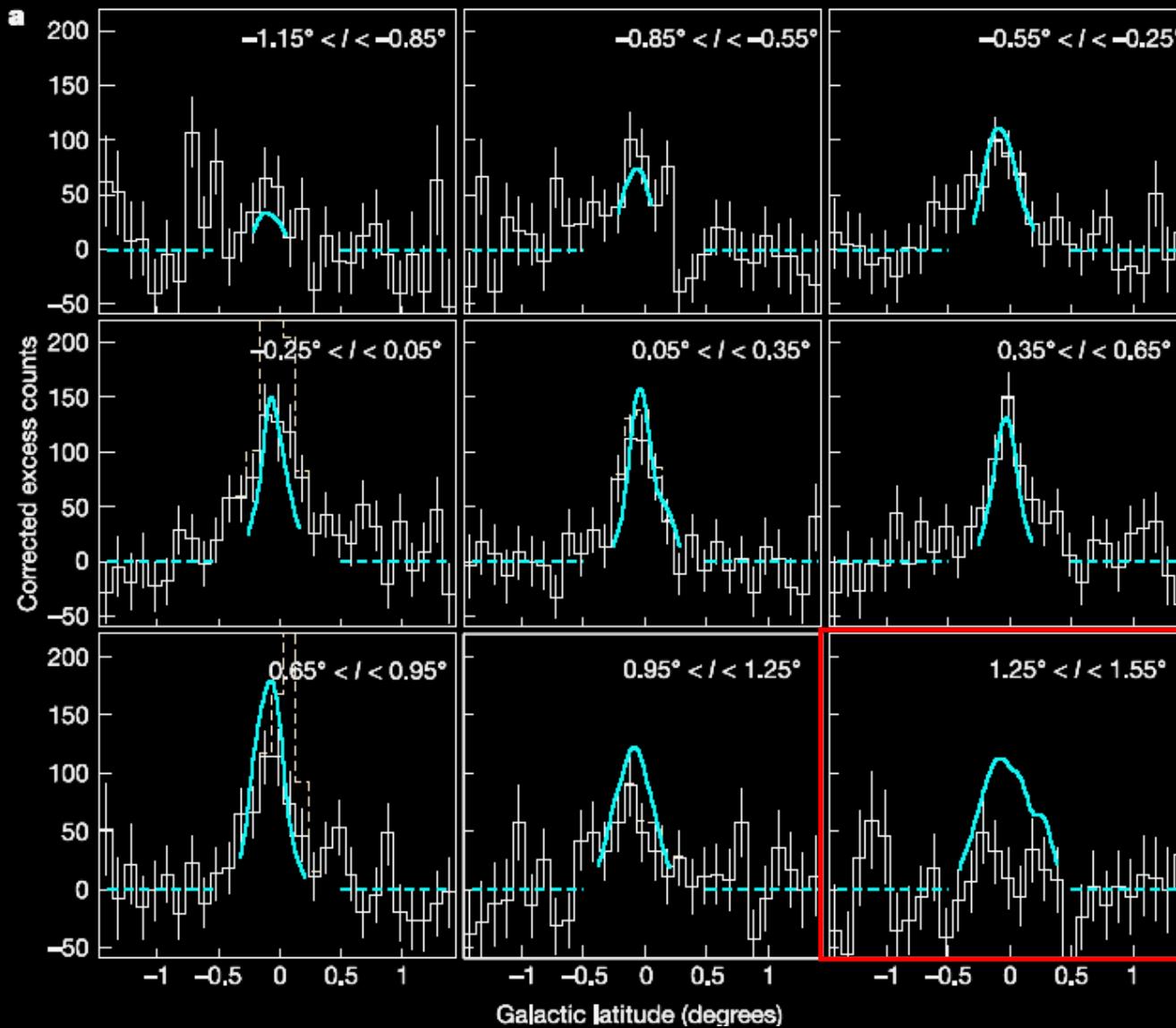


Diffuse Emission in the GC Region





GC diffuse: TeV-Flux vs Gas Density



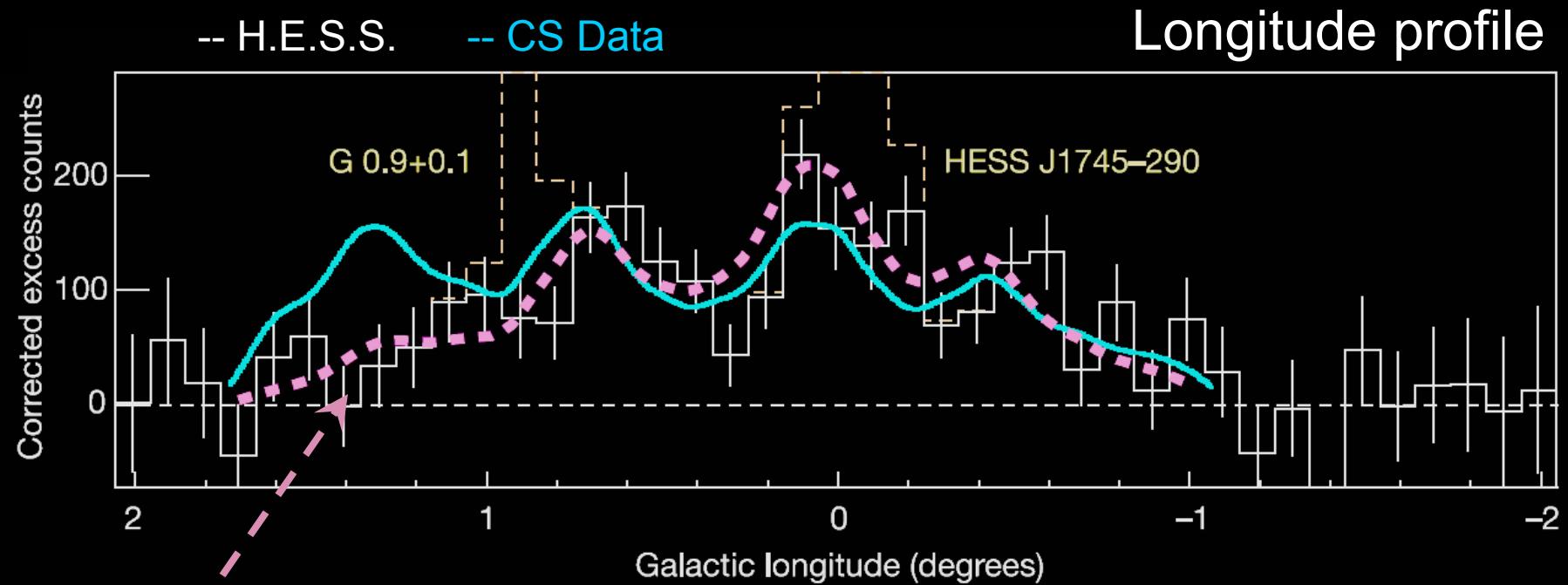
Latitude profiles

- H.E.S.S.
- CS Data

TeV - CS:
→ highly correlated



GC diffuse: TeV-Flux vs Gas Density



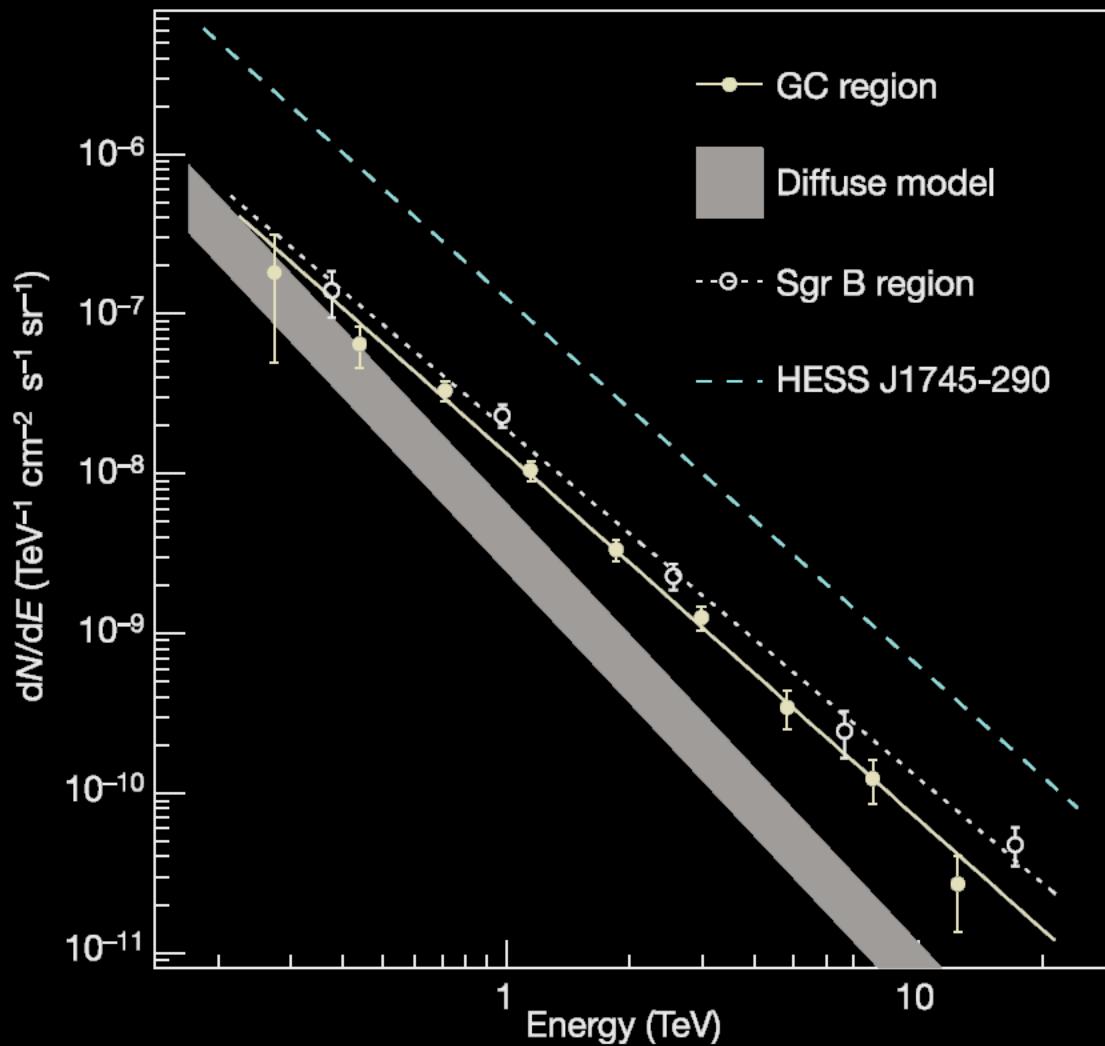
Diffusion Model:
Point Source at GC
~ 10000 yrs old

H.E.S.S., Nature (2006)

Interpretation:
we see (for the first time) interaction
between CR and molecular clouds
→ π^0 (production and decay)



GC diffuse: TeV-Flux vs Gas Density



CR flux is by
factor $\sim 3\ldots 9$ higher
than in solar neighborhood

Spectrum of CG:

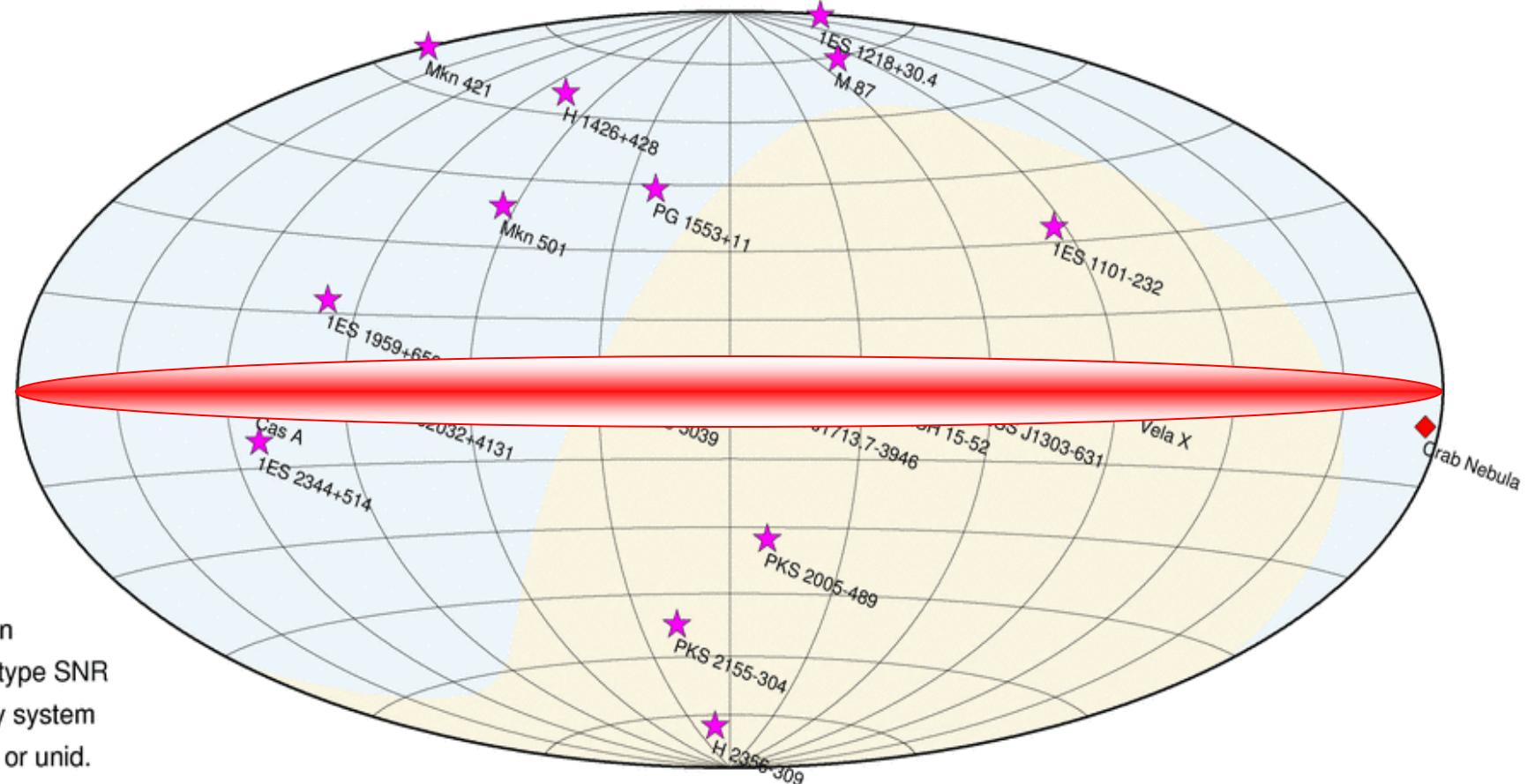
$$\Gamma = 2.29 \pm 0.07 \pm 0.2$$

($\Gamma = 2.7$ solar sys)

The High-Energy Gamma Ray Sky (2006)

(Galactic coordinates)

Galactic Sources



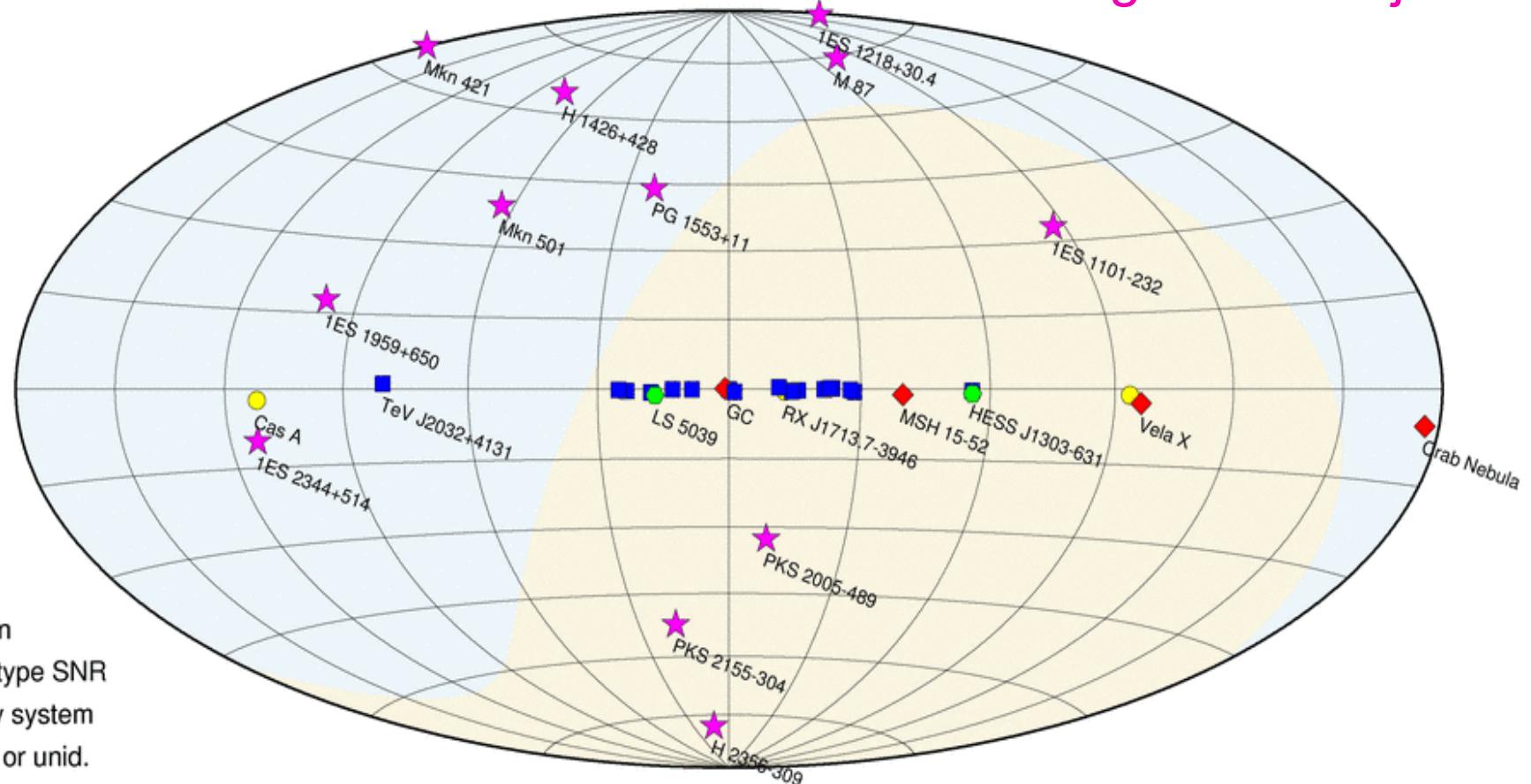
Background colours indicating northern / southern sky

Courtesy K.Bernlöhr, MPI-K

The High-Energy Gamma Ray Sky (2006)

(Galactic coordinates)

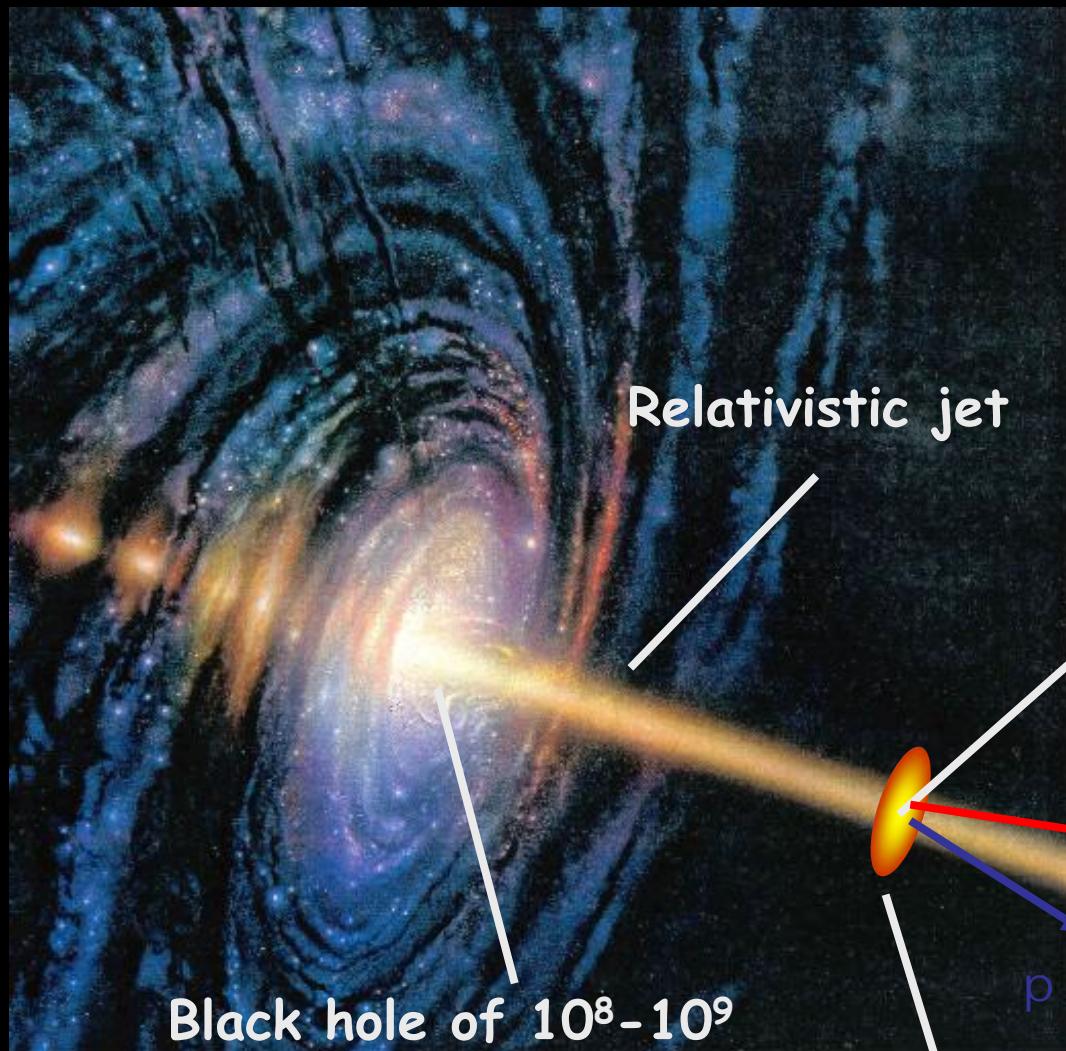
Extragalactic Objects



Background colours indicating northern / southern sky

Courtesy K.Bernlöhr, MPI-K

Gamma Ray Emitting Blazars: The Picture



"Blob" with
Lorentz factor γ_B, δ

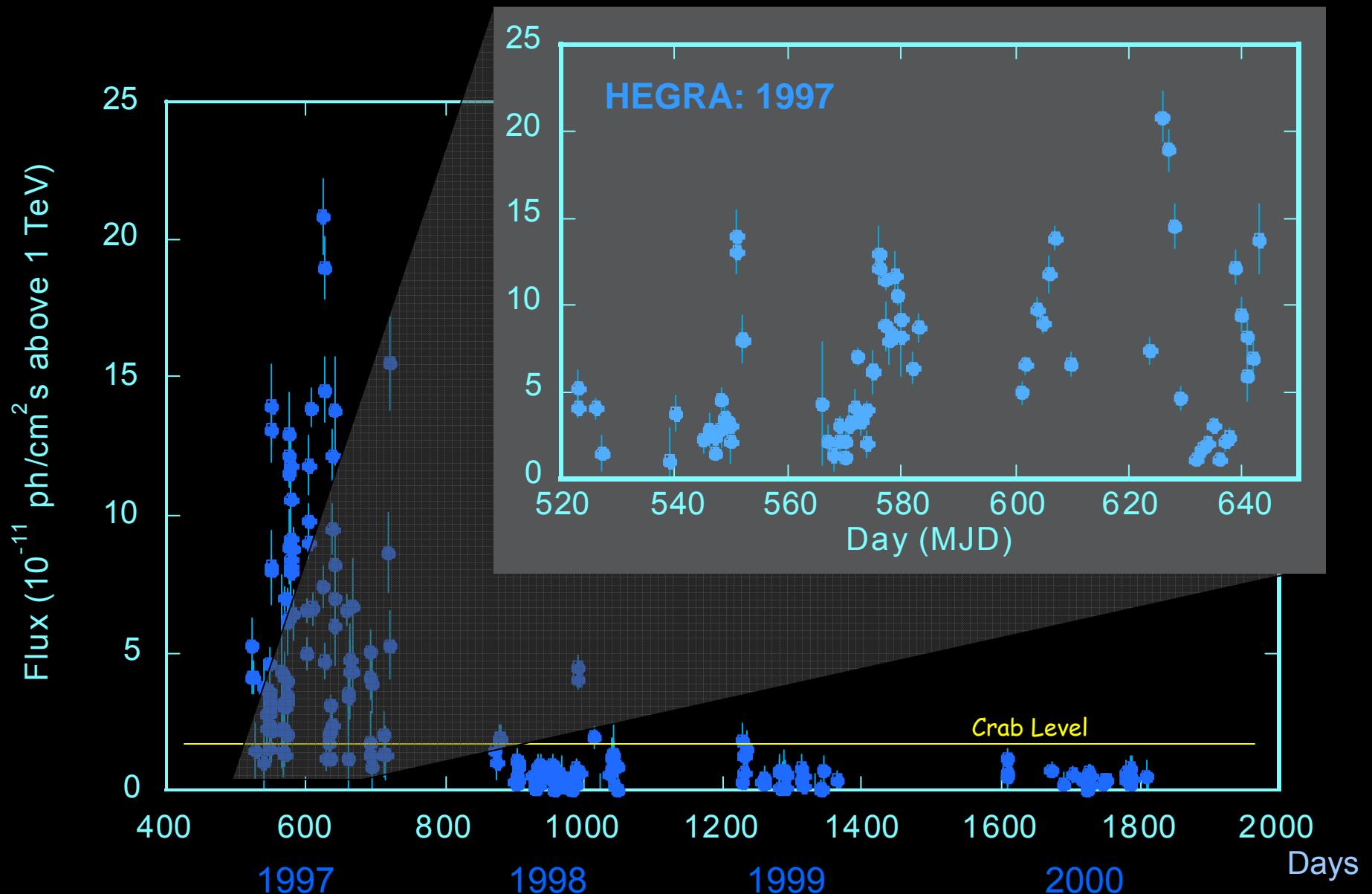
- Compact core, high luminosity brighter than host galaxy
- Non-thermal spectrum
- Radioloud
- Polarized \rightarrow synchrotron
- Highly variable (\sim h...y)

Accelerated
Particles w/ $\gamma \gg \gamma_B$

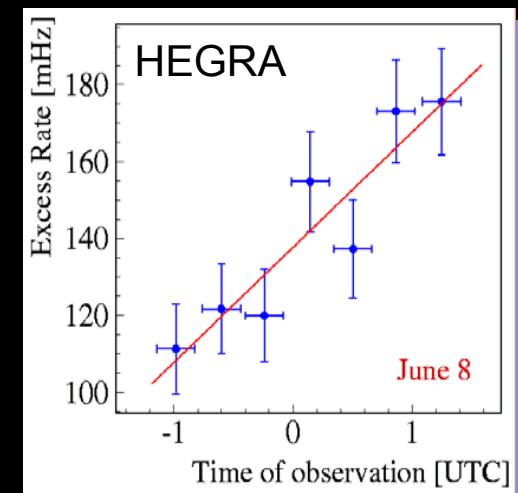
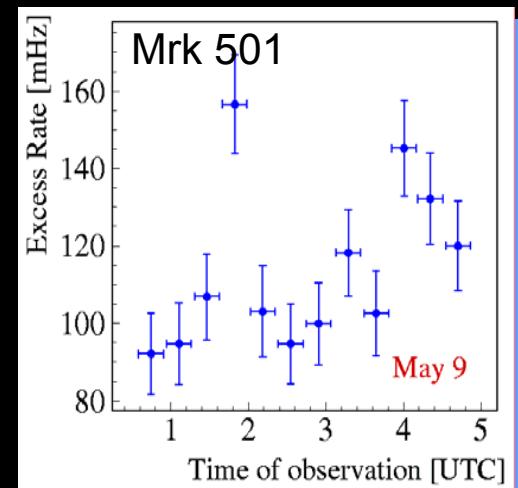
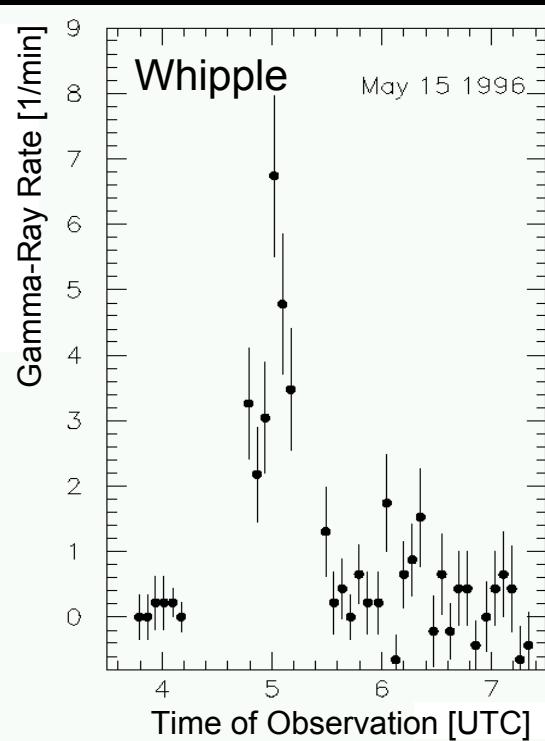
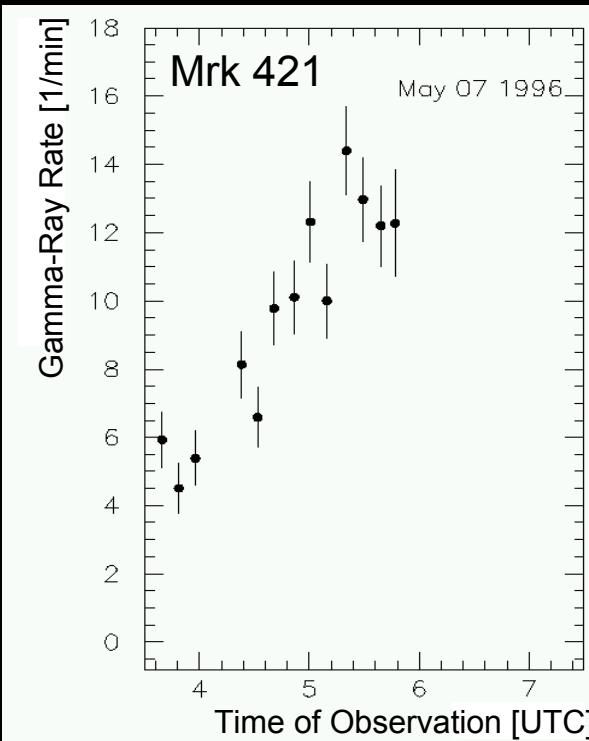
Beamed Radiation
„amplified“ intensity
shorter timescales



Mrk 501: Diurnal Light Curve



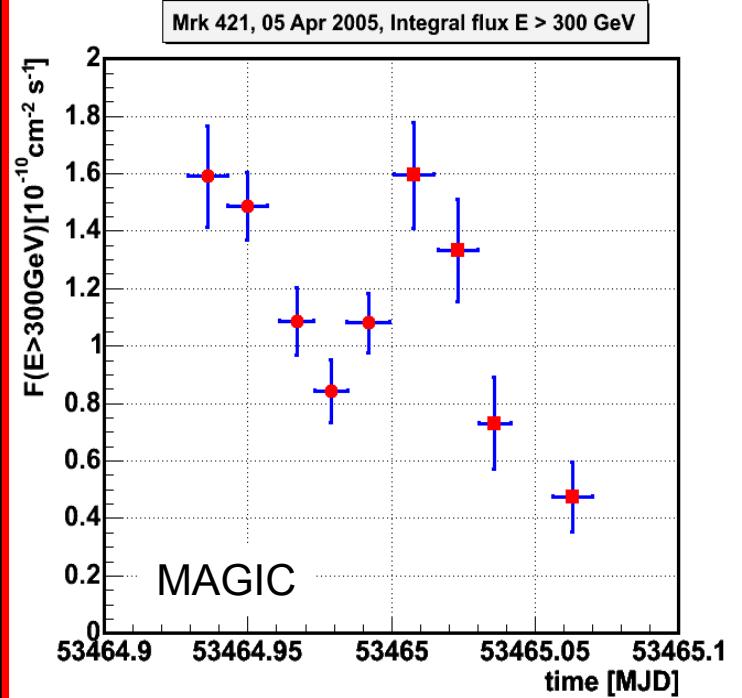
Mrk501, Mrk421: Intra-night Variability



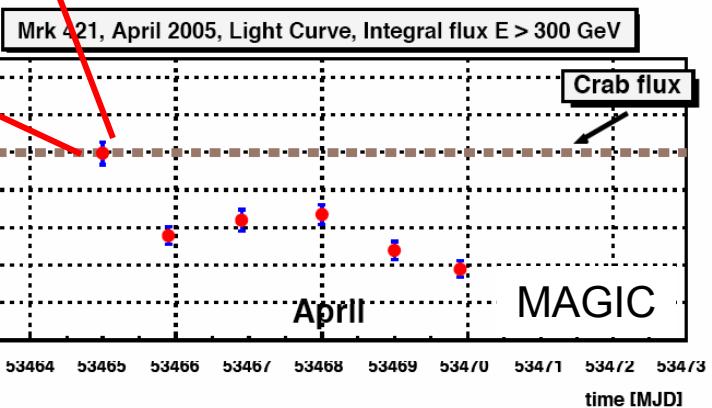
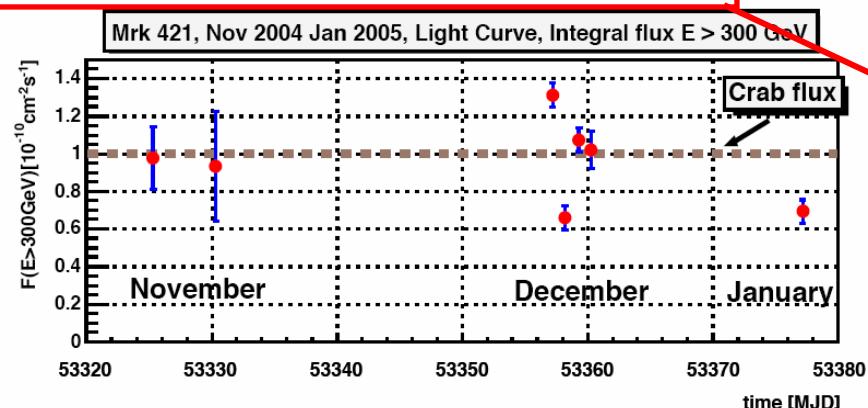
Shortest flare: ~ 30 min
Rise/fall ~ 15 min

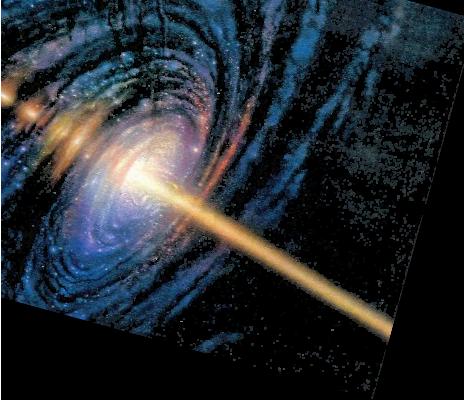
τ_{double} ~ 4 hours

Mrk501, Mrk421: Intra-night Variability

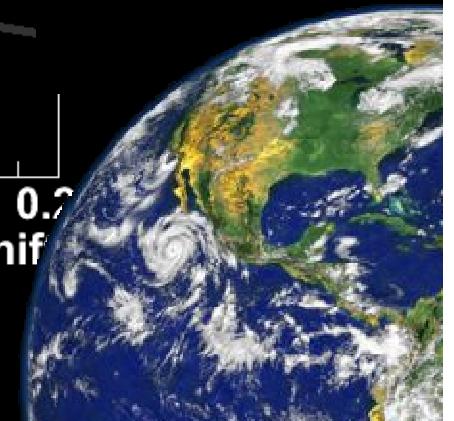
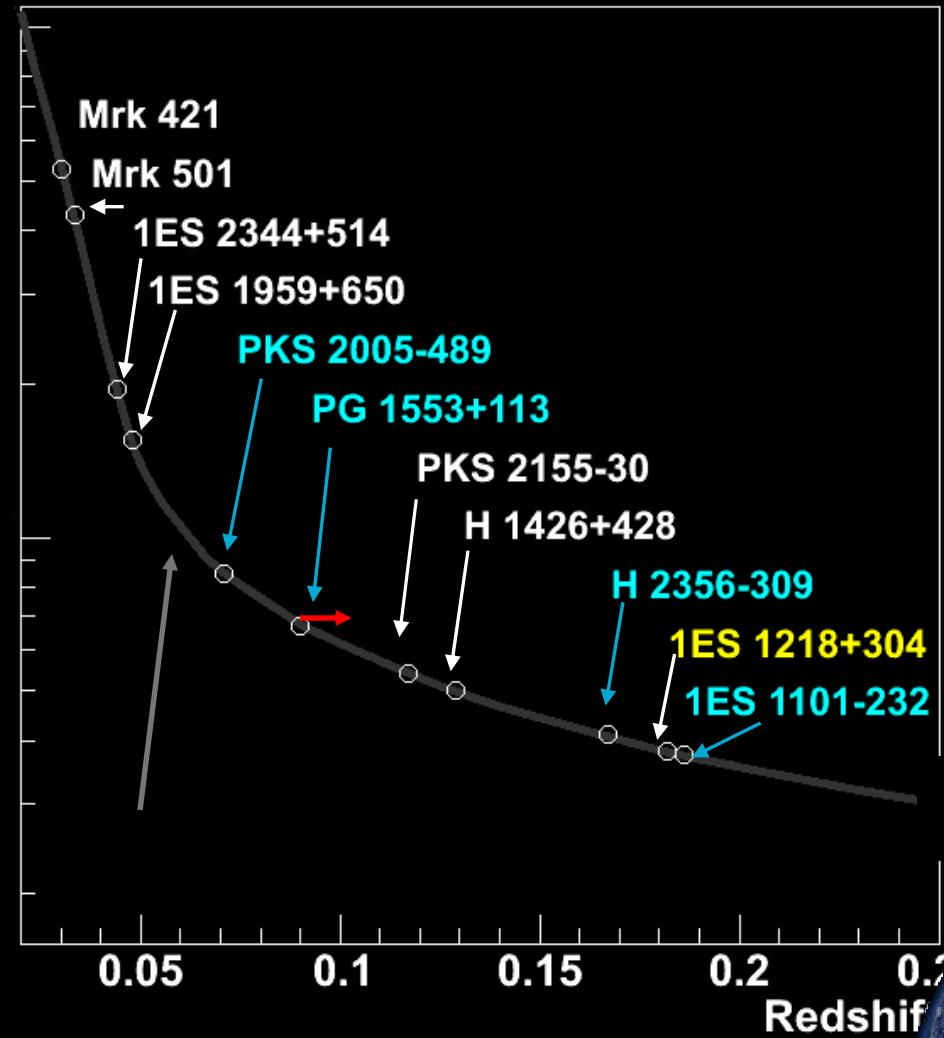


Source Radius:
 $r < 0.5 c \delta \Delta t \sim 10^{16} \text{ cm}$

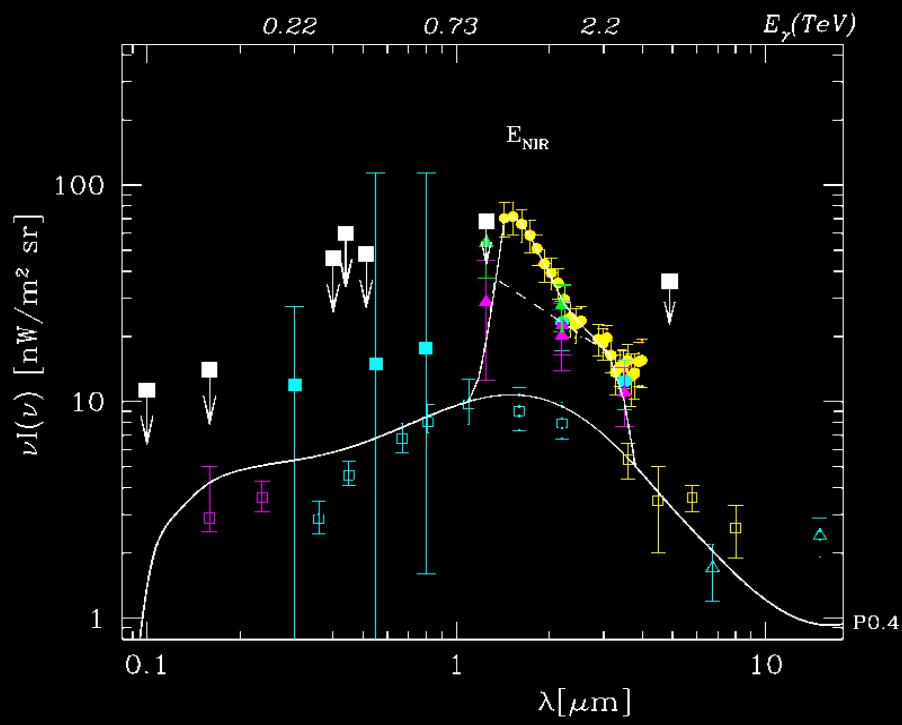
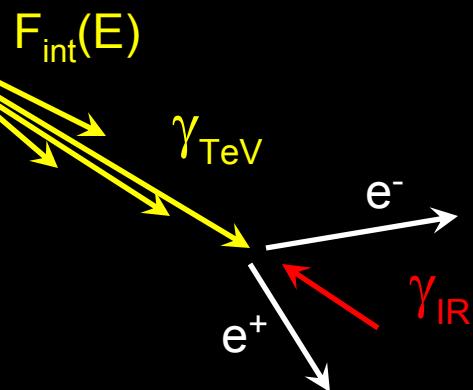
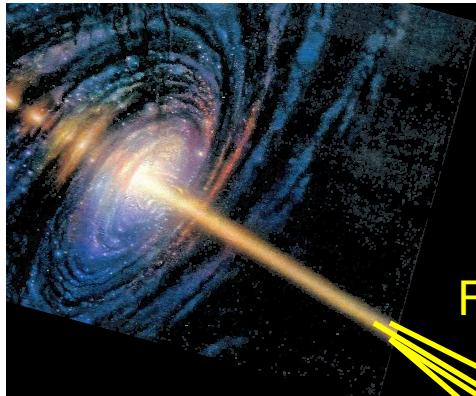




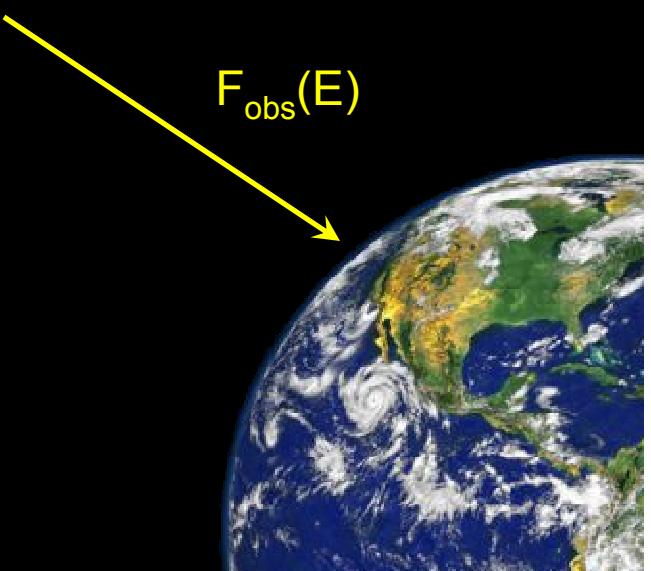
11 TeV Blazars detected so far



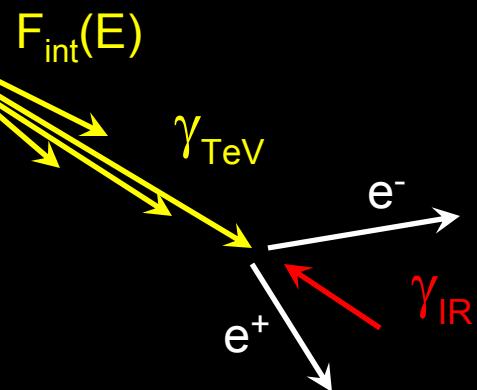
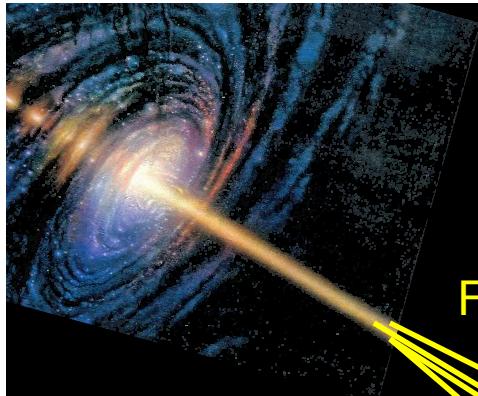
The Extragalactic Background Light



- Diffuse infrared background contains information on history of star and galaxy formation
- Experimental uncertainty > x2
- Direct measurement difficult



The Extragalactic Background Light

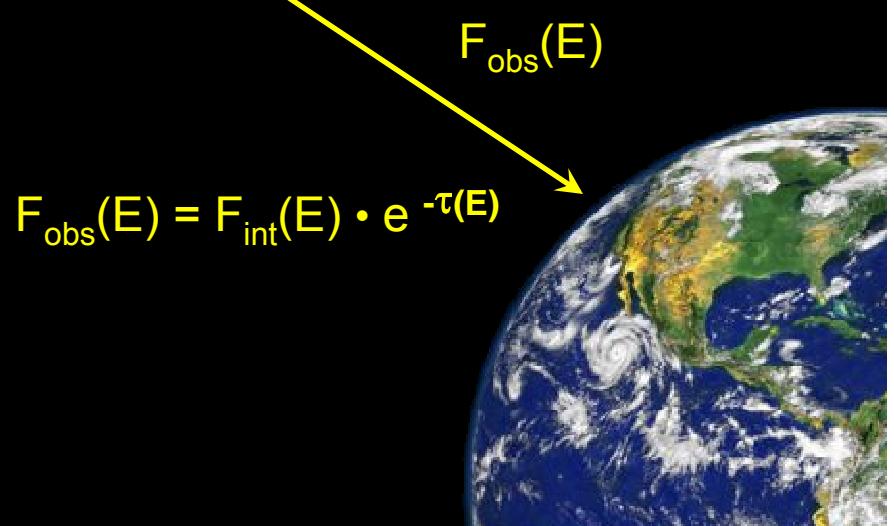
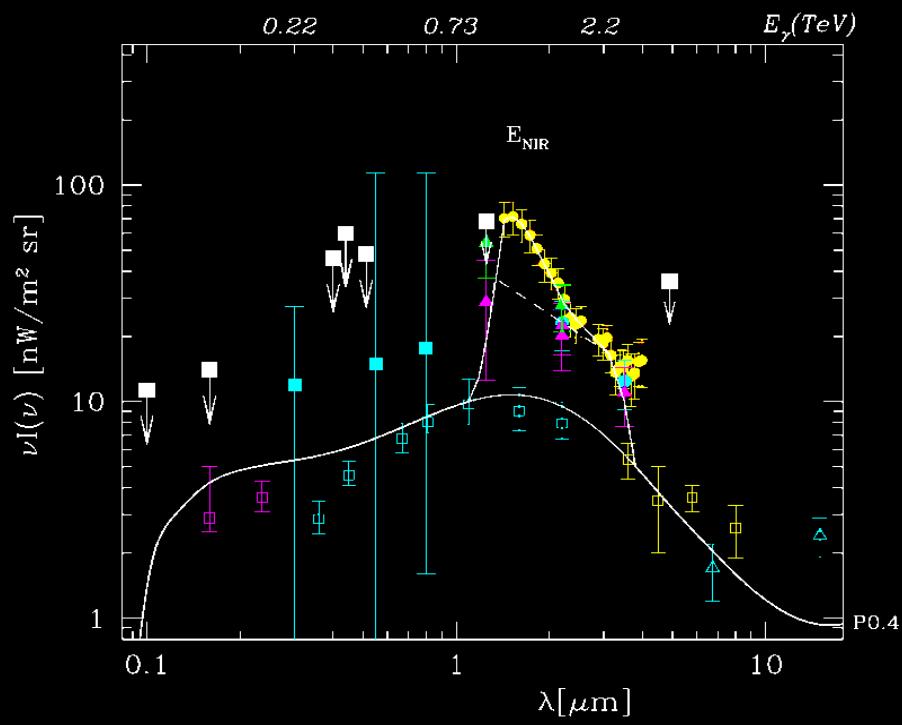


Cross Section peaks:

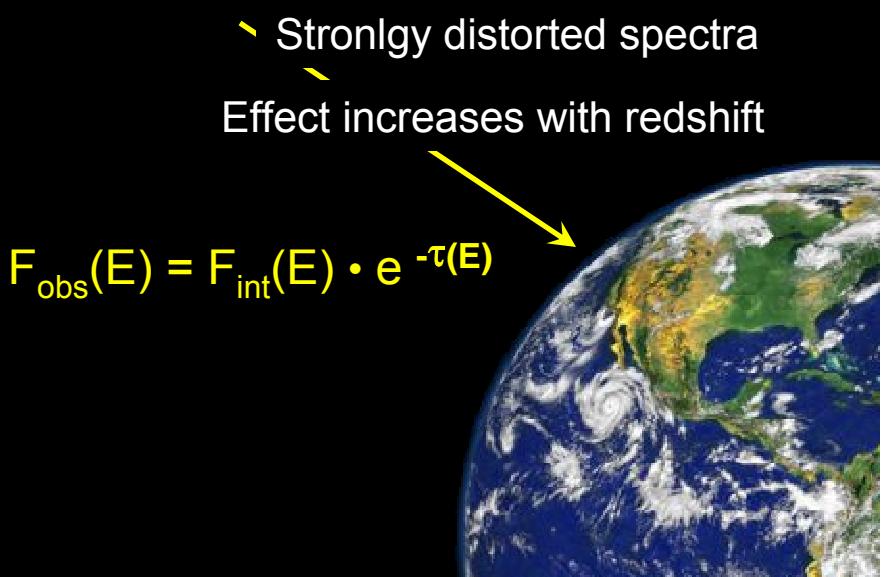
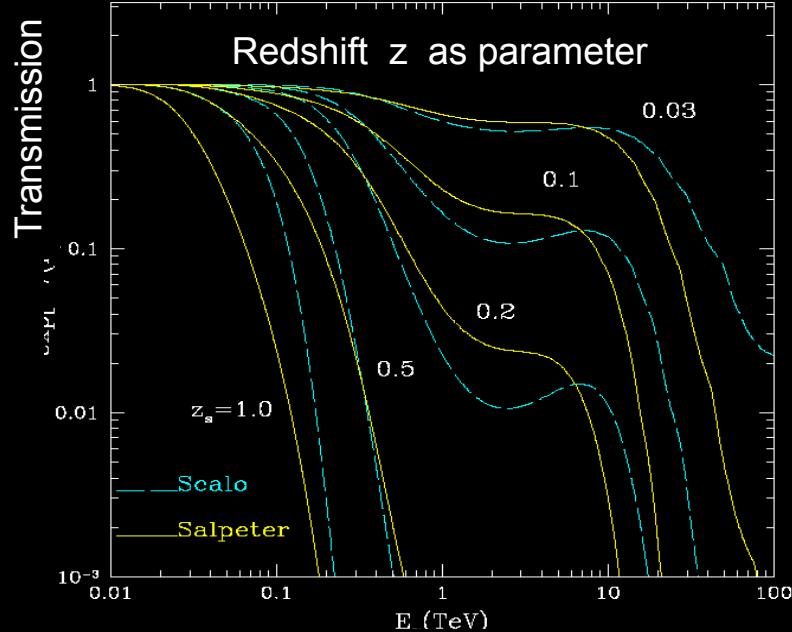
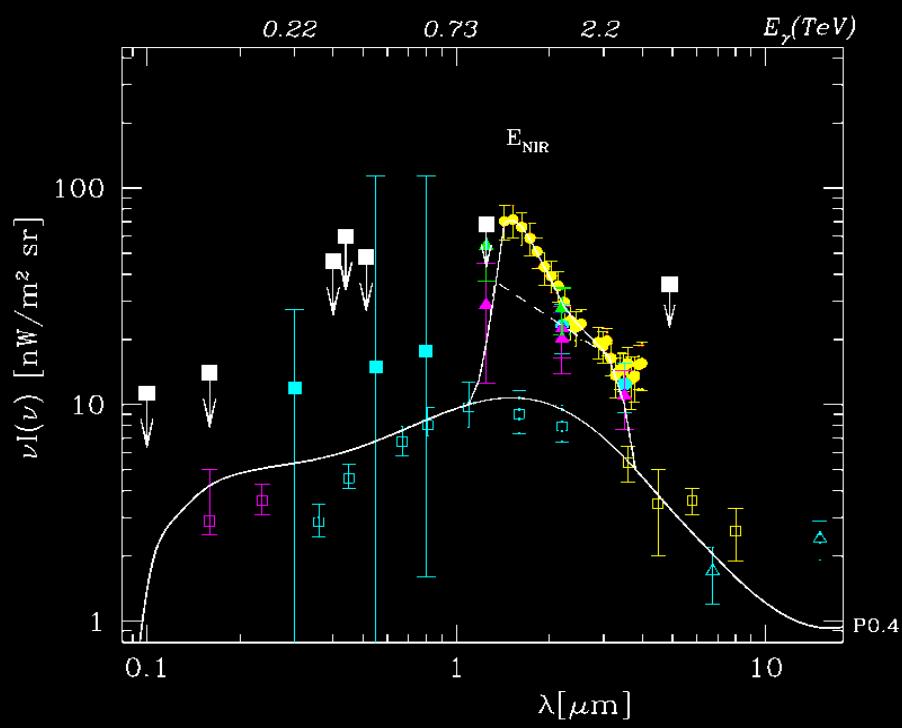
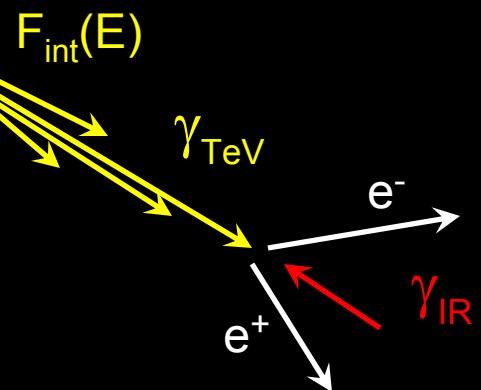
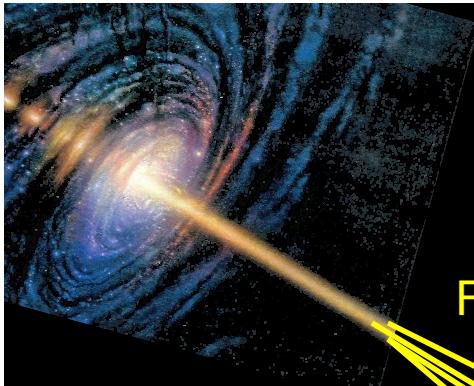
$$\lambda \sim 1.4 E_{\text{TeV}} [\mu\text{m}]$$

(width $\sim 0.5 \lambda$)

Close Energy Correspondance:
IR - TeV



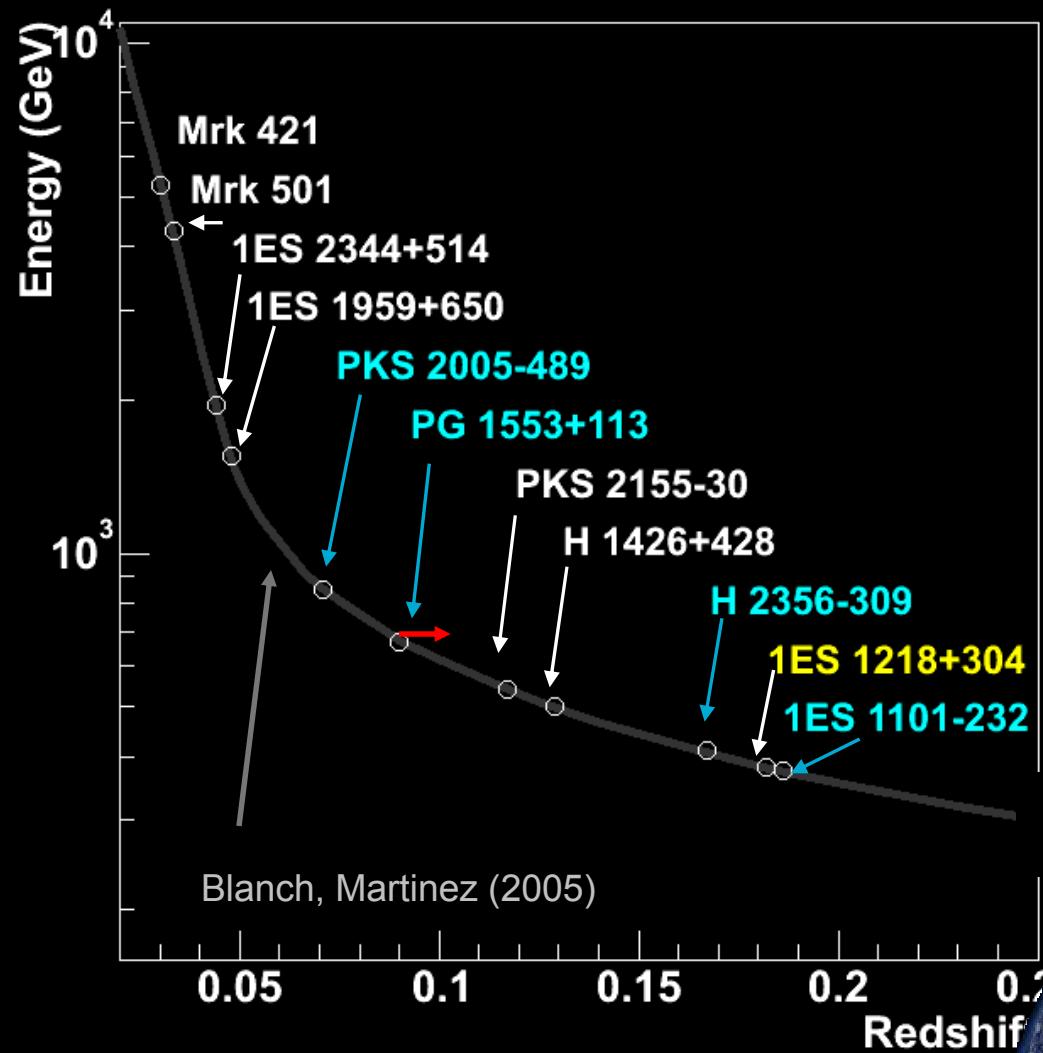
The Extragalactic Background Light



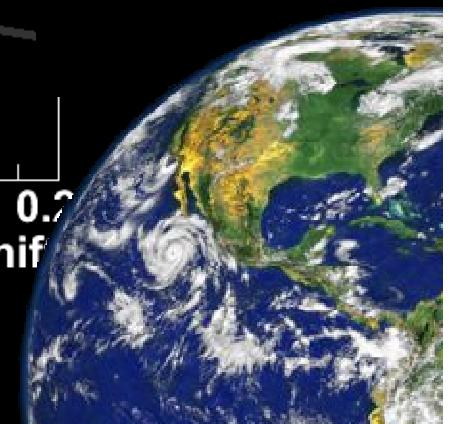
Gamma-Ray Horizon due to EBL

1ES 2356-309
1ES 1101-232

show relatively hard spectrum



Recently Discovered by:
H.E.S.S.
MAGIC

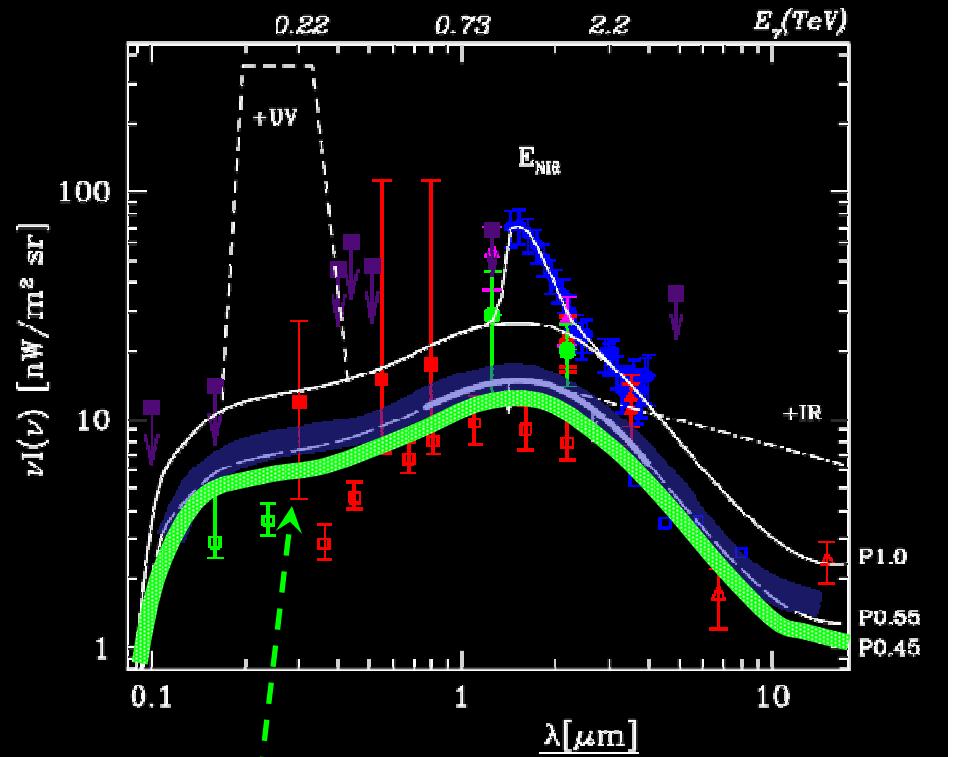
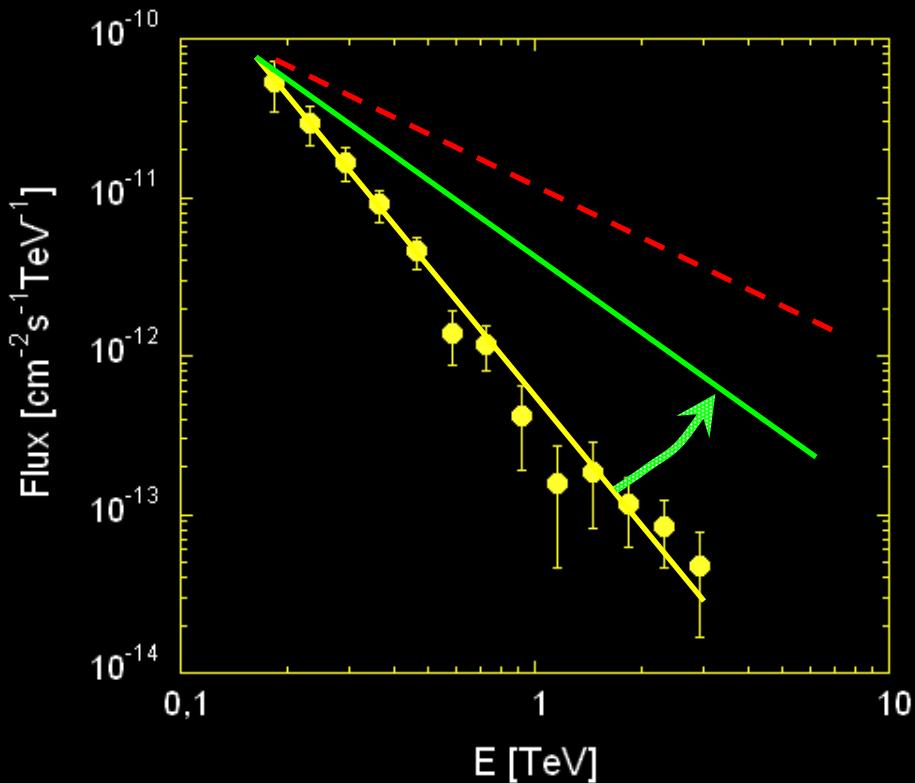


Derive Upper Limit on EBL



Assumption:
intrinsic spectrum of
blazars can't be harder than

$$\Gamma = 1.5$$



Parameterization
EBL spectrum

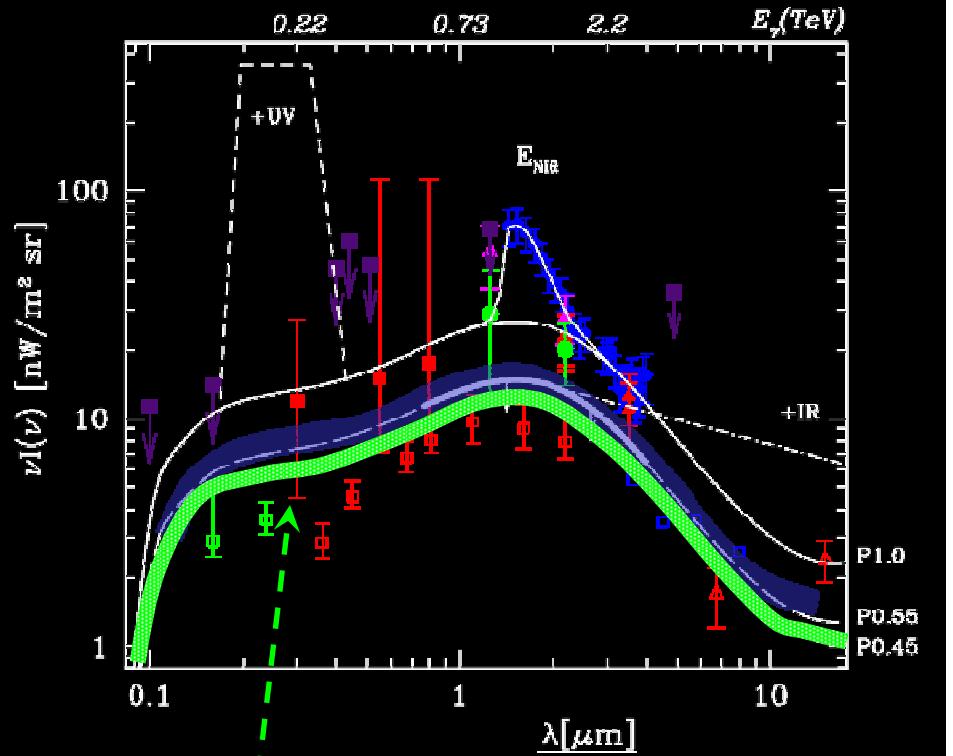
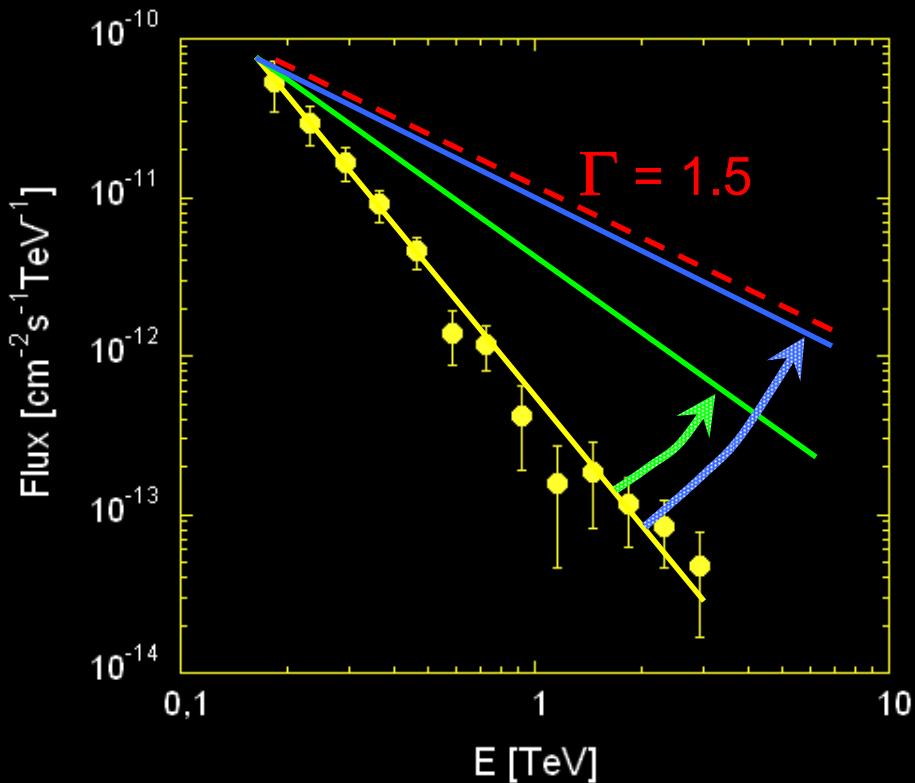


Derive Upper Limit on EBL



Assumption:
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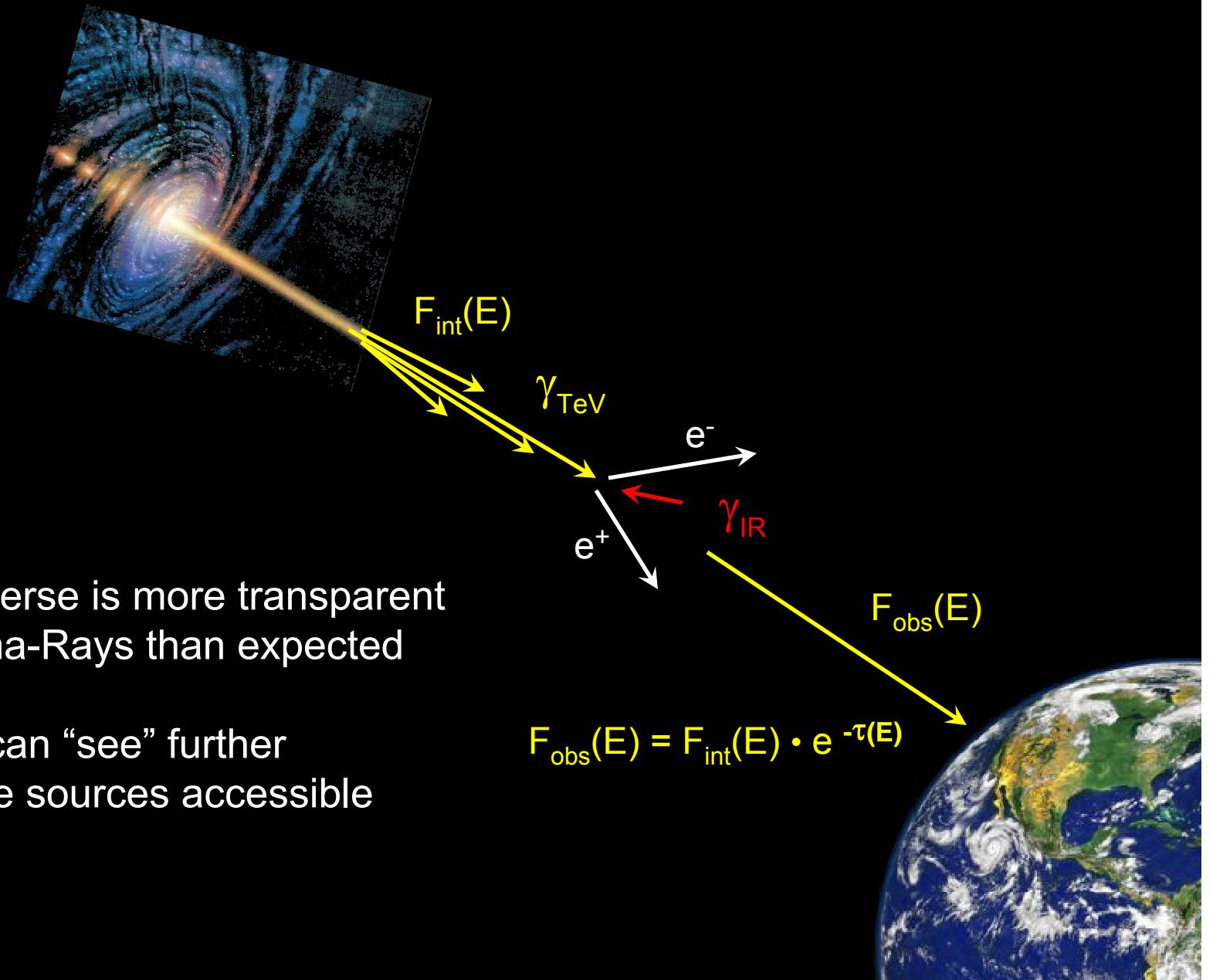


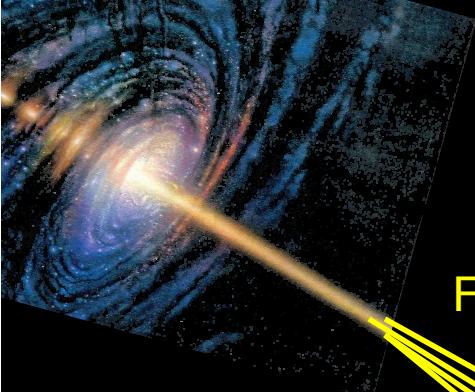
Parameterization
EBL spectrum

→ Nature (2006, soon)



The Good News ...

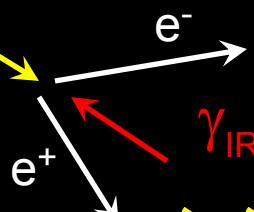




The Good News ...

$F_{\text{int}}(E)$

γ_{TeV}



$F_{\text{obs}}(E)$

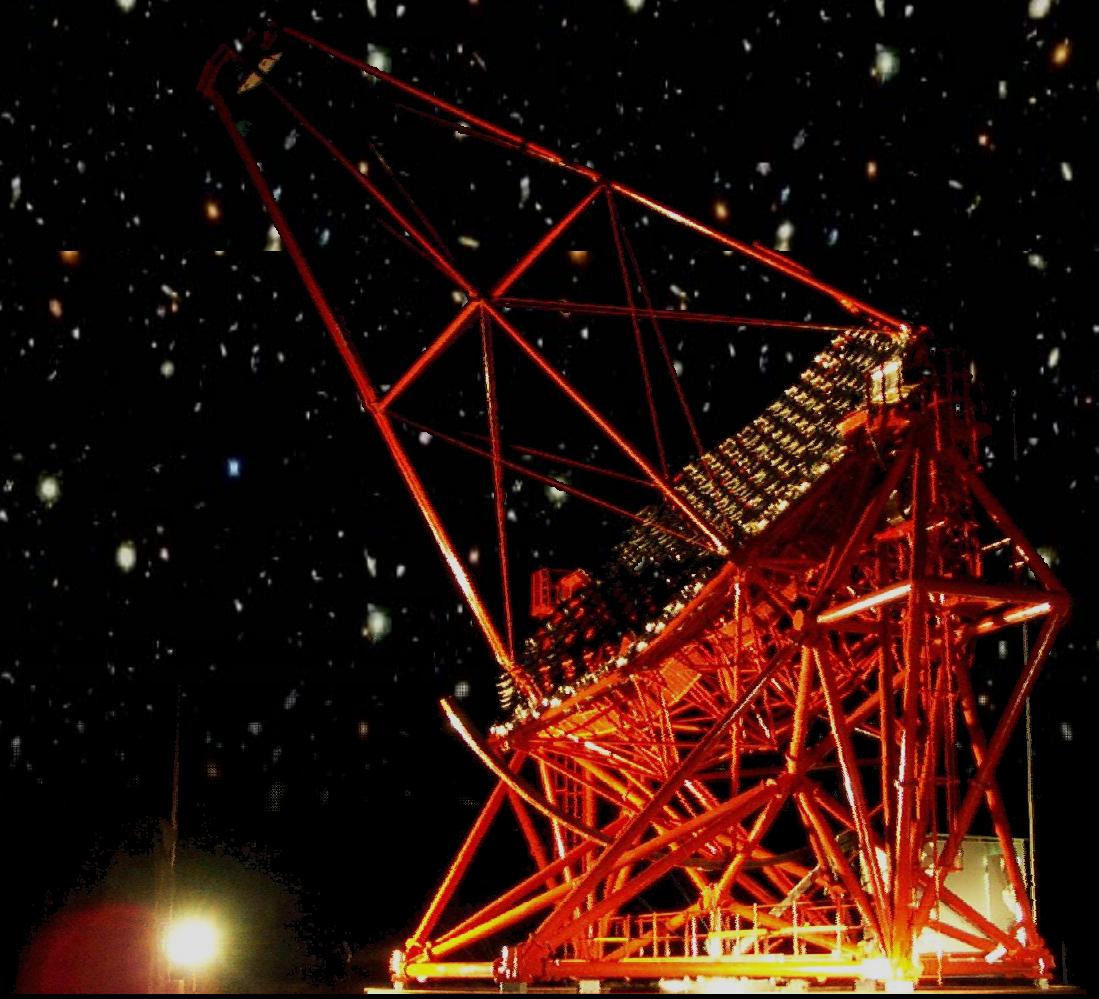
$$F_{\text{obs}}(E) = F_{\text{int}}(E) \cdot e^{-\tau(E)}$$

The Universe is more transparent
to Gamma-Rays than expected

- we can “see” further
- more sources accessible



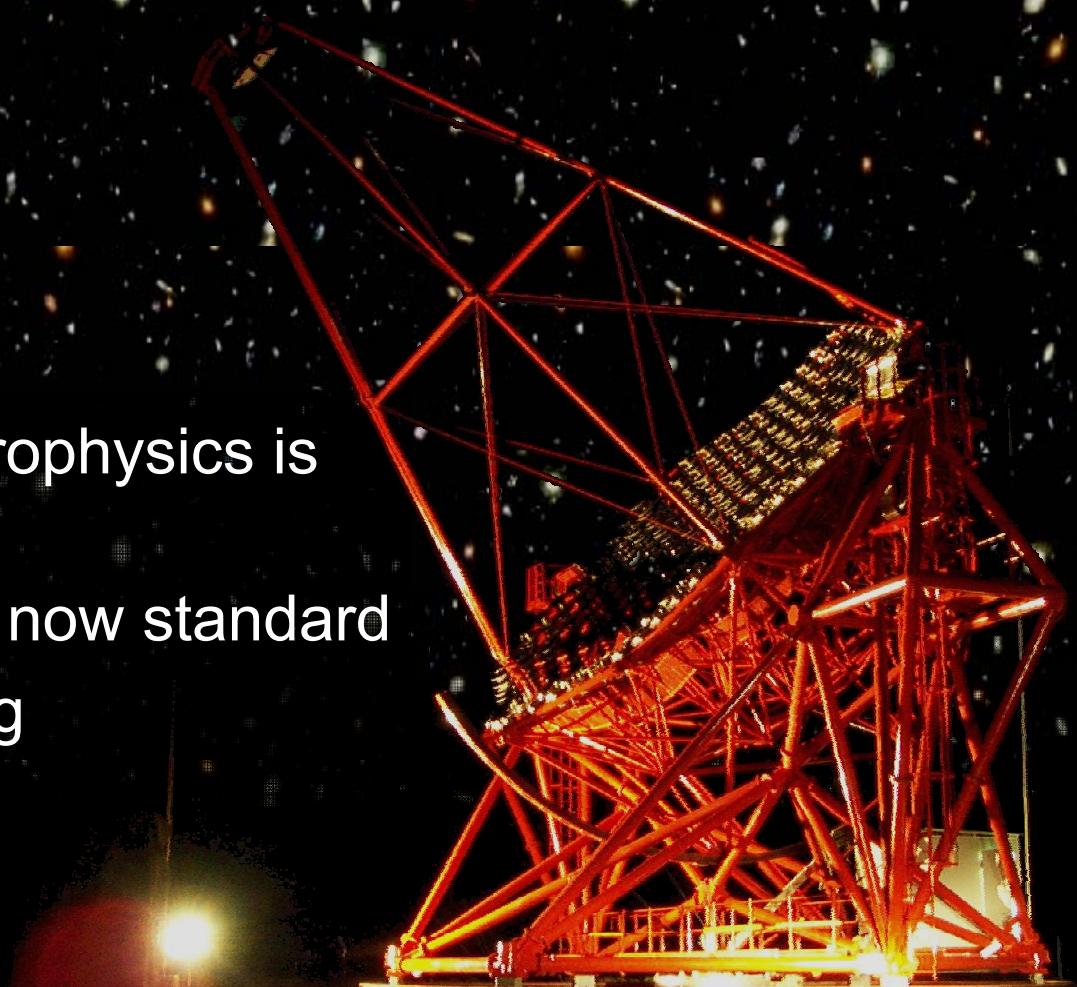
Ground-based Gamma-Ray Astronomy
is on its way !!!

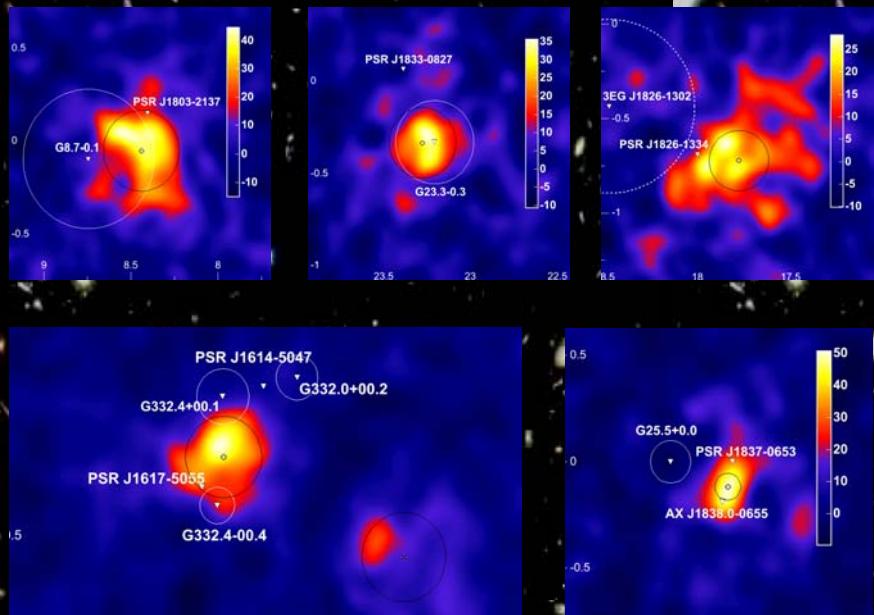


From Searching the Cosmic Particle Accelerators

- Ground based γ -ray astrophysics is on its way
- Precision measurement now standard
- Exciting physics awaiting

G.Hermann, MPIK

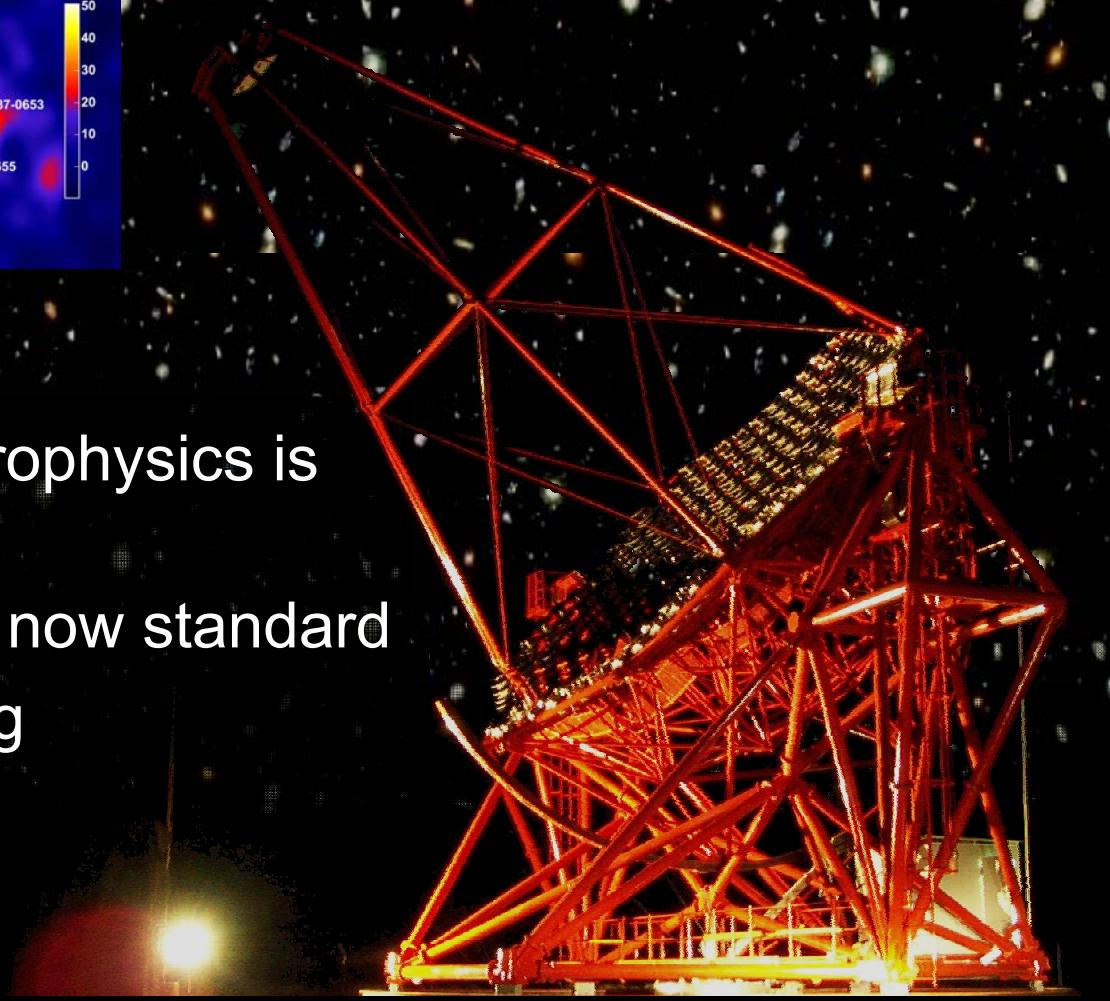




Finding the Cosmic Particle Accelerators

- Ground based γ -ray astrophysics is on its way
- Precision measurement now standard
- Exciting physics awaiting

G.Hermann, MPIK



WWW-links and other material

Links to some ground-based experiments:

H.E.S.S.	www.mpi-hd.mpg.de/HESS
MAGIC	wwwmagic.mppmu.mpg.de
VERITAS	veritas.sao.arizona.edu
CANGAROO	icrrhp9.icrr.u-tokyo.ac.jp/c-iii.html
MILAGRO	www.ianl.gov/milagro
Tibet_AS	www.icrr.u-tokyo.ac.jp/em/index.html

Page with links to (almost) all types of Cosmic Ray / Gamma-Ray / Neutrino Experiments:

www.mpi-hd.mpg.de/hfm/CosmicRay/CosmicRaySites.html

H.E.S.S. publications:

www.mpi-hd.mpg.de/HESS --> Publications

Reviews / Overviews:

T.WEEKES: "The Atmospheric Cherenkov Imaging Technique for
Very High Energy Gamma-ray Astronomy"
astro-ph/0508253

Books: T.WEEKES: "Very High Energy Gamma Ray Astronomy", (2003)
ISBN: 0750306580

F.A.Aharonian: "Very High Energy Cosmic Gamma Radiation" (2003)
ISBN: 9810245734